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THE TRANSIENT SUBMERGENCE OF OIL SPILLS: TANK TESTING AND MODELLING

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THE TRANSIENT SUBMERGENCE OF OIL SPILLS:

TANK TESTS AND MODELLING

by

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ABSTRACT

Based on theory and wind/wave tank test results, process equations incorporating oil properties and sea conditions have been developed to predict: whether or not a particular oil slick will break up into slicklets or blobs; the size of the resultant slicklets and blobs; whether or not they are overwashed by water and to what extent; the maximum transient submergence depth of the slicklets and blobs; and their distribution as a function of depth. These process equations have been incorporated into an oil spill fate and behaviour computer model that predicts oil spill spreading, evaporation, emulsification, natural dispersion and, now, transient submergence. The process equations were also simplified to allow quick estimates to be made for residual fuel oil spills and a range of emulsion mat sizes.

RÉSUMÉ

Selon la théorie et les résultats expérimentaux obtenus en bassin d'étude de l'interaction du vent et de la houle, nous avons construit des équations dans lesquelles entrent les propriétés des hydrocarbures et l'état de la mer afin de prédire: si une nappe se dissociera ou non en flaques ou en globules; les dimensions de ces flaques et globules; leur ennoiement éventuel et sa profondeur; la profondeur maximale de submersion transitoire des flaques et des globules ainsi que leur répartition verticale. Nous avons amalgamé ces équations à un modèle du devenir et du comportement des nappes qui permet de prédire l'étalement, l'évaporation, l'émulsification, la dispersion naturelle des hydrocarbures et, afin, la submersion transitoire. Nous avons en outre simplifié ces équations en vue d'une estimation rapide des nappes résiduelles et de la distribution des dimensions des agrégats d'émulsion.

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1. INTRODUCTION

Given appropriate oceanographic conditions and oil properties it is possible for oil slicks to submerge beneath the sea surface. This renders detection, tracking and countermeasures for the spill extremely difficult if not impossible. The objective of this study was to validate and extend the work of previous studies on the formation and submergence of "sinkable" oil forms, and to develop operationally useful process equations to predict the conditions under which an oil spill might be expected to submerge.

1.1 HISTORICAL PERSPECTIVE

Several oil spill incidents in the past have had reports of sinking or disappearance of oil slicks. These include the Arrow (Forrester 1971) in which large drops of emulsified Bunker C were detected at depths of up to 80 m; the US/NS Potomac (Petersen 1978) in which the Bunker C formed pancakes that eventually sank; the IXTOC-1 blowout during which large subsurface mats of weathered mousse were observed (Payne and Phillips 1985); the Kurdistan incident which sparked the current interest in oil submergence (C-CORE 1980); the Katina incident in which the heavy fuel oil submerged only to appear on shore later (Rijkwaterstaat 1982); and the recent Thuntank 5 incident in Sweden in which 36 to 40 tons of heavy fuel oil sank in icy waters (OSIR 1987).

The common thread among these incidents is that all involved very low or neutrally buoyant oils or water-in-oil emulsions that, through weathering, formed into particles or mats ranging in size from a millimetre or less to several metres. The criteria for oil submergence seem to be: low or neutral buoyancy and the formation of particulate oil forms.

1.2 THE STATE-OF-THE-ART

Several previous studies have addressed various aspects of sinking or submergence of oil spills. Juszko et al. (1983) and Juszko (1985) have extensively reviewed both the oceanographic conditions conducive to oil submergence and the occurrence and frequency of those conditions in Canadian waters. Mackay et al. (1985 and 1986) presented an excellent literature review on the subject and conducted both small-scale tests with oils and mid-scale tests with surrogates that identified the mechanisms that result in oil submergence. These two most recent studies laid the groundwork for this study.

Other studies (WSL 1978; WSL 1981; S.L. Ross 1984, 1985) have addressed the behaviour and weathering of oils that, when spilled, form into mats and droplets. A major ESRF-funded study of "waxy" oil behaviour, which includes extensive analyses of pan and droplet formation, "skin" formation and meso-scale tank tests is nearing completion (S.L. Ross and DMER 1987). This latest study has addressed several of the research needs identified in the penultimate study on oil submergence (Mackay et al. 1986).

1.3 RATIONALE FOR THE STUDY

To date, the small and mid-scale studies on oil pan/droplet formation and submergence have included extensive theoretical treatment, some small-scale testing and limited meso-scale testing with surrogates. What was required was extensive meso-scale testing with actual oils to validate the previous studies and permit the development of operationally useful equations to predict what percentage of the "slick" is submerged at various depths as a function of environmental conditions. Because a key issue in any spill is its detection at sea, it was proposed that the meso-scale tests also include an assessment of the capability of simple remote sensing technologies to detect the submerged oil.

1.4 REPORT CONTENTS

Section 2.0 of this report details the experimental methods used in the wind/wave tank tests. Section 3.0 presents and discusses the results and the development of predictive process equations. Section 4.0 describes how the process equations were incorporated into a computerized oil fate and behaviour model and presents some predicted results. This section also contains predictive nomographs based on the process equations. Conclusions and recommendations, in Section 5.0, complete the report.

2. STUDY METHODS

2.1 TEST TANK

The experimental portion of the study was conducted in a wind-wave tank (Figure 1) 11 m long, 1.2 m wide and 1.9 m high. The tank was filled with approximately 10,000 L of fresh water to a depth of 0.85 m. Saltwater was not used as it was thought that the oil-water density difference (i.e., buoyancy) rather than absolute densities was the key to submergence processes. This significantly reduced the complexity of the testing.

The tank was fitted with a submerged air-bubbler system in the glass-walled test section to prevent the sticky oils from quickly adhering to the sides of the tank; this permitted test runs of several hours. Waves were generated in the tank by a paddle at one end driven by a continuously variable speed electric motor; Table 1 lists the wave characteristics measured (photographically) for the paddle settings used in the tests.

TABLE 1

TEST WAVE CHARACTERISTICS

WAVE GENERATOR SETTING	WAVE HEIGHT (m)	WAVE LENGTH (m)	STEEPNESS RATIO
40	0.12	4.25	0.055
50	0.14	3.25	0.086
60	0.15	3.20	0.094
80	0.23	1.45	0.33*

* waves were breaking in the test section

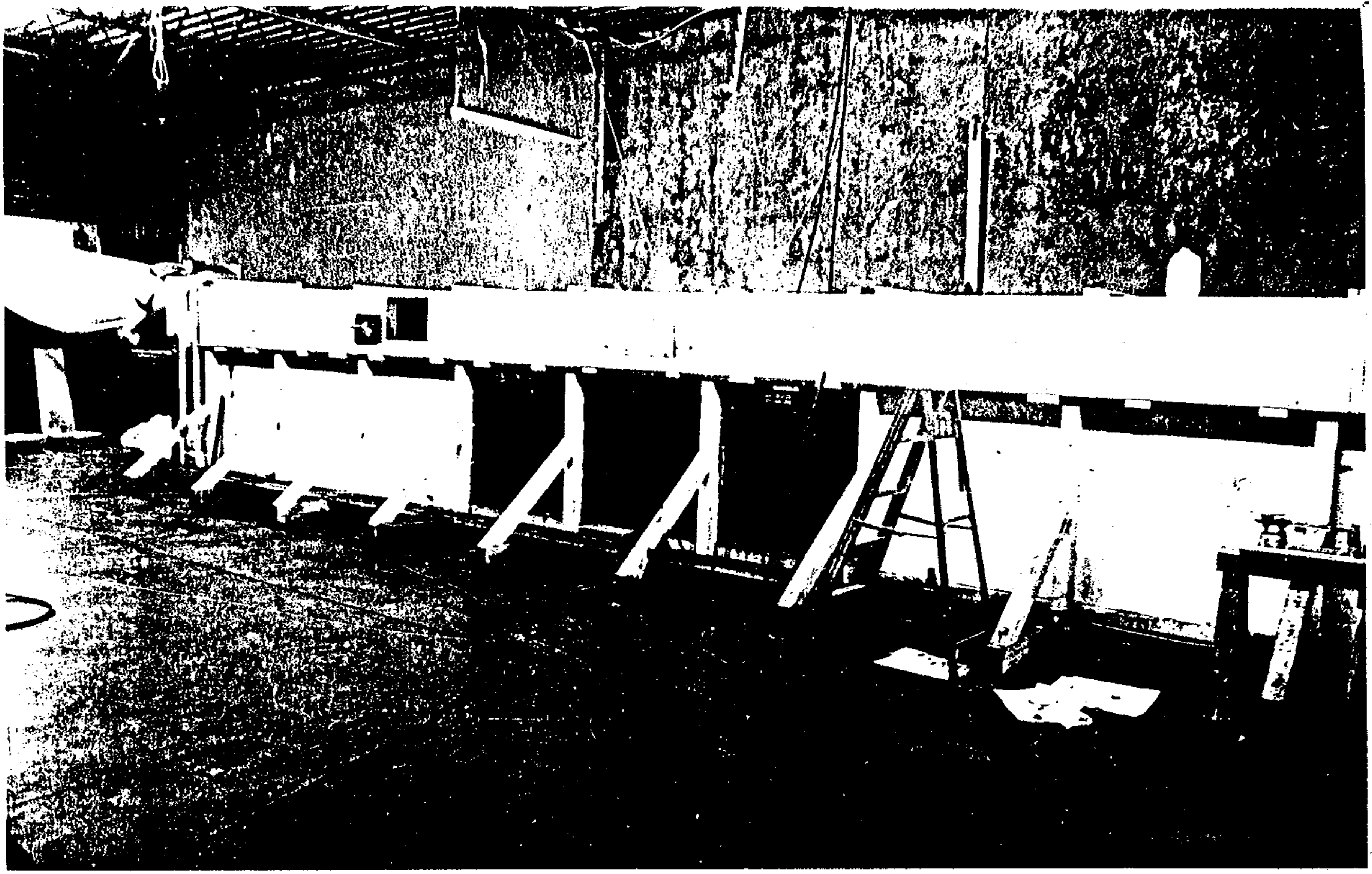


Figure 1 - wind/wave tank

Winds, generated by a blower mounted in the wind tunnel above the tank, were used only for the first few tests; winds were excluded as a test variable for reasons discussed in Section 3.0.

2.2 TEST OILS

Since the majority of Canadian spills involve Bunker C (fuel oil number 6), an oil that offers the greatest potential for sinking, the test program concentrated on it. The properties of the uncut heavy Bunker C used in this study are given in Table 2. The density, and concomitantly viscosity, of the Bunker C were varied by diluting the oil with automotive diesel fuel (see also Table 2). In order to investigate the effect of oil viscosity independent of buoyancy, a waxy Grand Banks crude oil (J-34) was emulsified with different percentages of 35 part per thousand (ppt) artificial seawater.

TABLE 2

TEST OIL PHYSICAL PROPERTIES

OIL	TEMPERATURE (^{o}C)	DENSITY (kg/m^3)	VISCOSITY (mPas = cP)
BUNKER C	10	1018	111,000
	5	1022	752,000
	1	1025	2,310,000
AUTO DIESEL	10	831	2.9
	5	835	3.5
	1	837	3.8
J-34	10	881	12,000
(from S.L. Ross	5	885	42,000
and DMER 1987)	1	888	not measured

2.3 TEST PROCEDURES AND ANALYTICAL TECHNIQUES

A typical test run was conducted as follows. The tank was filled with cold tap water to a depth of 85 cm. A sample of four hundred ml of the test oil was warmed to about 45°C (to facilitate pouring and initial distribution on the water surface), then poured onto a spill plate on the water surface; three or four distinct slicklets were created. Fifteen minutes were allowed for the temperature of the slicklets to equilibrate with the water.

The waves were then turned on at setting 40 (see Table 1); the bubbler was turned on once the slicklets moved towards the walls of the tank or began to drift out of the test section. The behaviour and position of the oil were recorded simultaneously by two video cameras (Figure 2): one positioned above the tank looking down on the test section and one under water at one end of the tank looking along the underside of the slicklets. Still photographs of oil behaviour were taken through the glass walled test section and visual observations were noted throughout each test.

After a 1/2-hour test period with the wave generator setting at 40, it was increased to 50. This procedure was repeated up to a wave generator setting of 80.

Samples for physical property analysis were obtained prior to each run for those tests involving Bunker C (since the change in properties of this oil with exposure is negligible) and after each run for those tests involving crude oil emulsions. Oil density was determined using a Parr Densitometer. Viscosities for the more viscous samples (>20,000 mPas) were determined at 1, 5 and 10°C using a Brookfield viscometer at a shear rate of 0.3 s^{-1}. The viscosities of the more fluid samples were measured, at the test temperature, using cross-arm viscometers. Although attempts were made to measure interfacial tensions using a ring tensiometer, these proved futile for most of the samples because of their high viscosity. Since it is known that interfacial tension varies only slightly as a function of oil type and

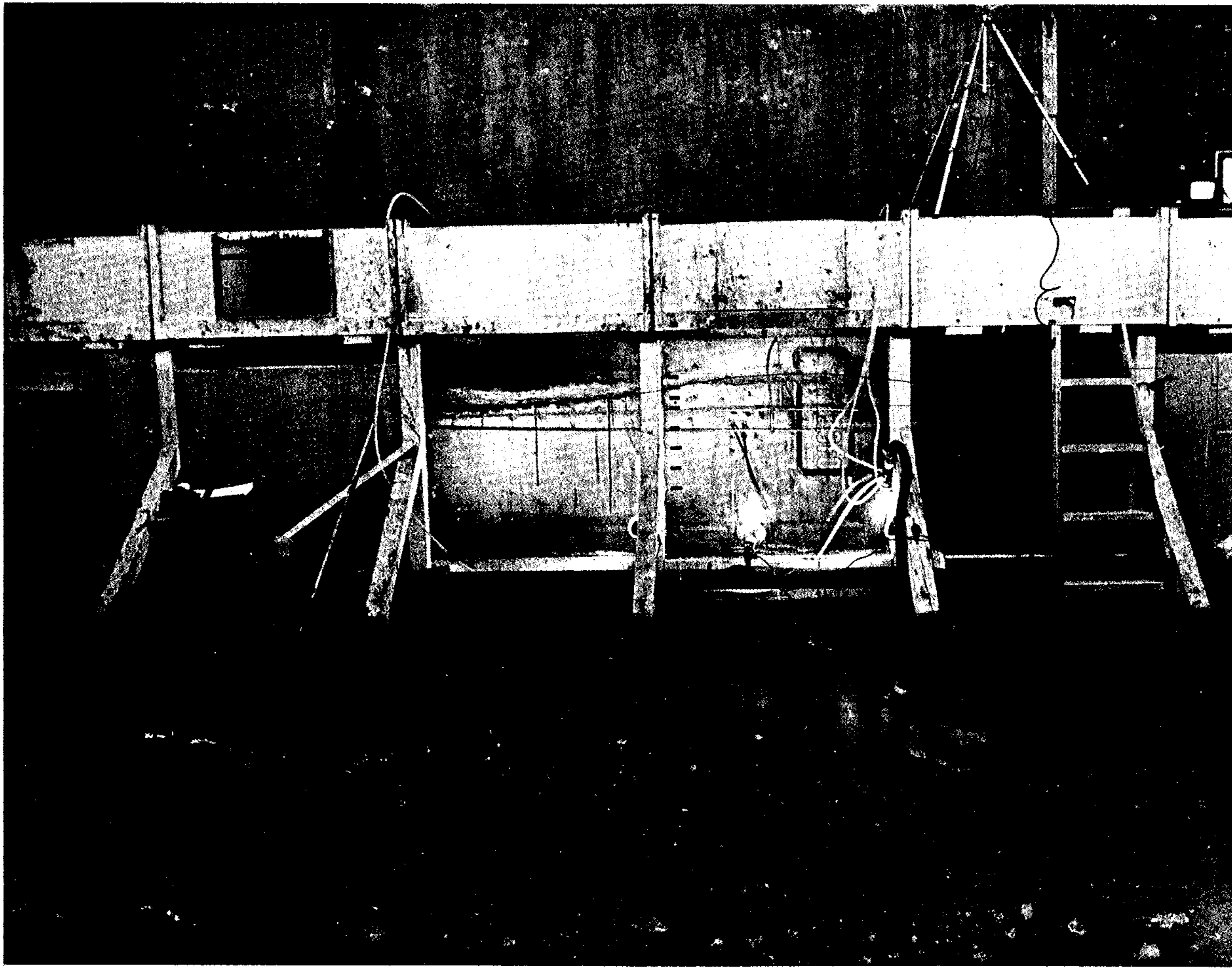


Figure 2 - closeup of test section

weathered state, no attempts were made to use more sophisticated techniques.

Although it had originally been planned to measure dispersed oil concentrations and drop sizes, this was abandoned when it was observed that, because of the low buoyancy and high viscosity of the test oils and emulsions, the drops of oil permanently suspended in the water were very large and widely separated. The usual technique for measuring dispersed oil concentration and drop size distribution involves sampling and analysing a small volume of water beneath the slick but is only valid if the small sample is considered to be representative of the whole system. This is the case for homogeneously dispersed oil involving small droplets but is not for heterogeneous distributions such as those observed in these tests.

3. RESULTS AND DISCUSSION

3.1 BLENDED AND EMULSIFIED OIL PROPERTIES

Table 3 lists the measured physical properties for the blended or emulsified oil used in each run. The buoyancy ratio (defined as the density difference between oil and water divided by the density of water) ranged from 0.001 (Runs A3 and A9) to 0.042 (Run A5); the oil viscosity ranged from 430 to 842,000 mPas.

TABLE 3
BLENDED AND EMULSIFIED OIL PROPERTIES

RUN	OIL TYPE*	TEST TEMPERATURE (°C)	DENSITY (kg/m^3)	VISCOSITY (mPas)
A1	uncut Bunker C	5.0	1022	752,000
A2	Bunker C/11% diesel	5.5	998	5640
A3	Bunker C/10% diesel	7	999	6280
A4	Bunker C/19% diesel	7.5	981	1480
A5	Bunker C/29% diesel	9	958	430
A6	Bunker C/5% diesel	4	1016	16,300
A7	Bunker C/14% diesel	4	994	2570
A8	J-34/71% salt water	5.5	980	842,000
A9	J-34/85% salt water	9	999	591,000
A10	J-34/78% salt water	9	990	666,000

* blended as mass percent

3.2 GENERAL DESCRIPTION OF TEST RUNS

A short description of the behaviour of the oil in each run is given.

Run A1. When the uncut Bunker C (density 1022 kg/m^3) was poured onto the quiescent water (density 1000 kg/m^3), it was surprising to note that the oil did not sink to the bottom of the tank but rather formed 20-30 cm diameter slicklets with thicknesses on the order of 1 to 2 cm (Figure 3). On closer inspection, it was revealed that the top of the slicklets was 1 to 2 mm below the water level; the interfacial tension between the two immiscible liquids created a convex meniscus allowing the oil to displace more water than its volume would normally permit. This was confirmed with subsequent bench scale tests in which the floating denser oil began to sink immediately after dispersant was added to the water.

Regardless of this interesting phenomenon, as soon as the wave generator in the large test tank was turned on the oil began to sink. This happened in two stages: the first stage involved the slicklet thickening into pendant drops (Figure 4), and the second was the formation of long strings or tendrils as the bottom of the pendant drop sank and drew oil from the still floating slicklet (Figure 5). Eventually the upper slicklet was depleted and the oil lay on the bottom of the tank like random coils of rope. This also occurred in Run A6.

Run A2. In this run with an oil density of 998 kg/m^3 and viscosity of 5640 mPas, as soon as the waves, fan and bubbler were turned on, the oil formed into hockey puck size and shape globs that were continually overwashed by 5 mm of water (Figure 6).

It is worth noting that although the air bubbles were confined to the sides the water they entrained created a Langmuir type of circulation in the tank and "windrowed" the slicklets. In initial trial runs in the tank, without the bubbler system and with wind over the waves, it was observed that the slicks were also rapidly overwashed at the lowest wave heights and wind speed. In subsequent runs with the bubbler system on, the same

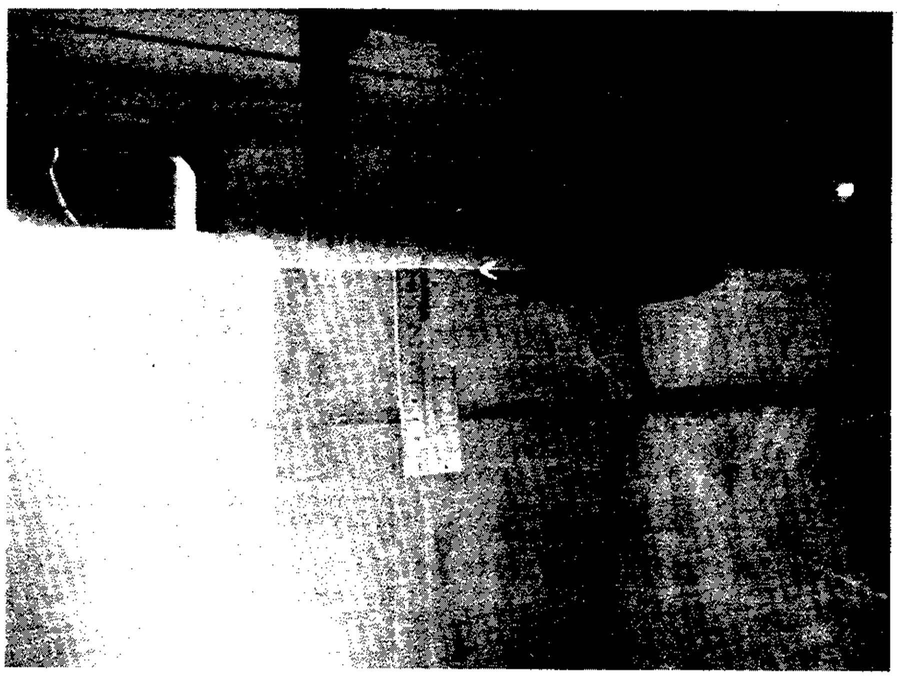


Figure 3 - Pre-test oil lens, Run A1

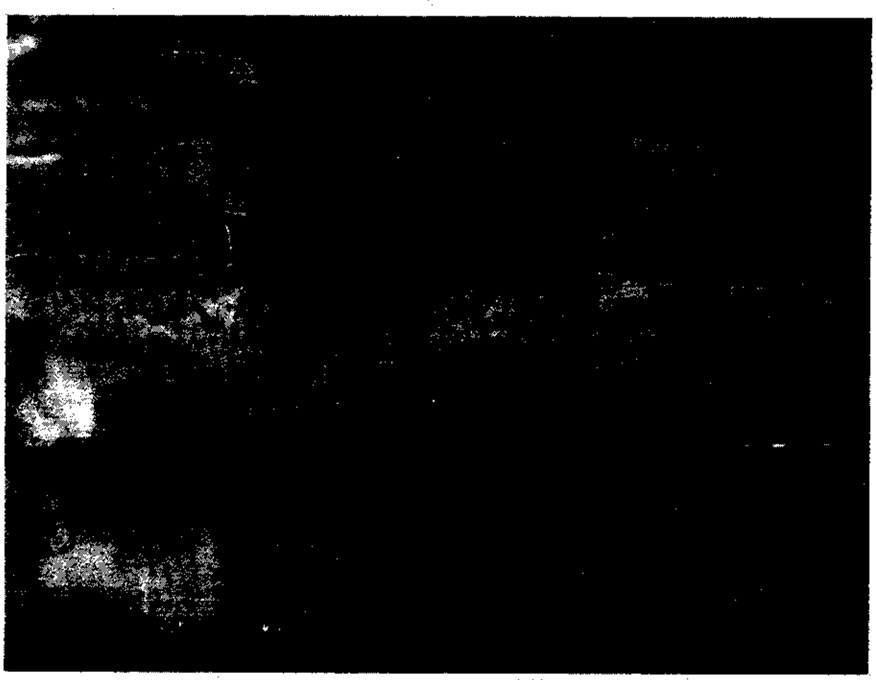


Figure 4 - Non-buoyant pendant oil, Run A1

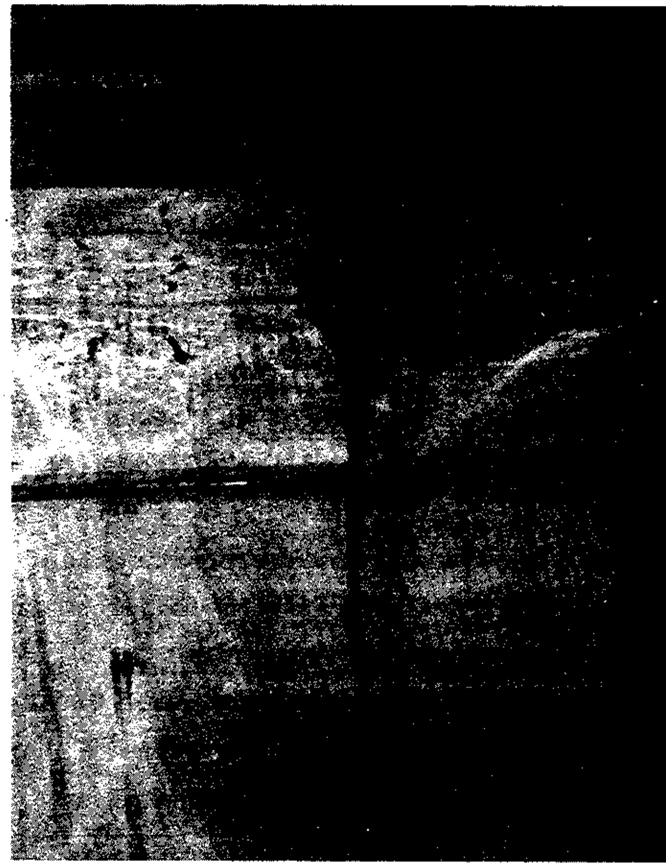


Figure 5 - Oil drop necking down, Run A1

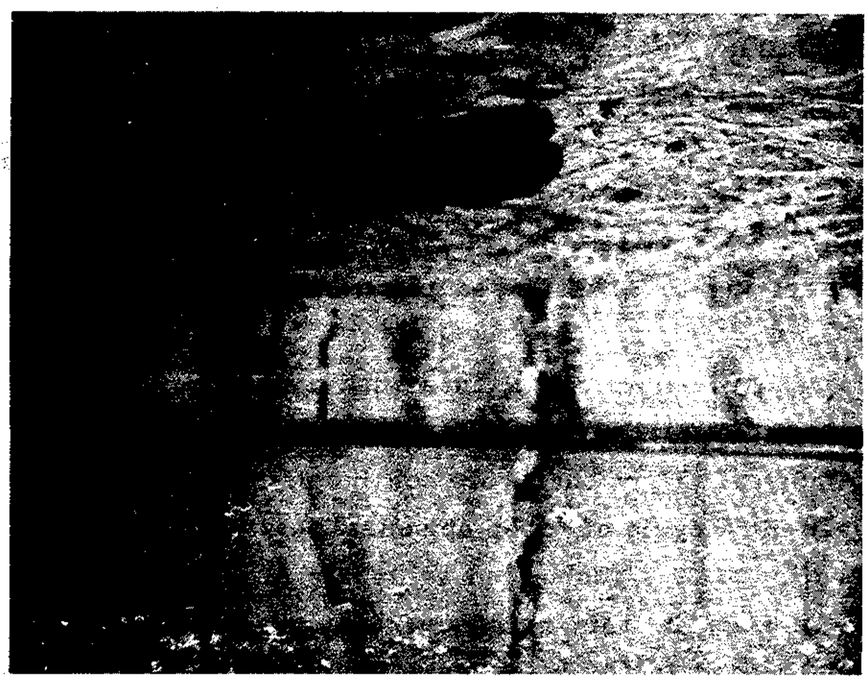


Figure 6 - Initial overwashing, Run A2

behaviour was noted but "windrowing" and overwashing occurred more rapidly. As well it was observed that the Langmuir type circulation was weak and could only draw down oil droplets that were on the order of a millimetre in diameter or less. Since Langmuir cells occur at sea (with downwelling velocities on the order of 0.85% of the wind speed at and below convergence lines or "windrows") it was decided that the bubbler system did not detract from the realism of the tests. Further, since it created a surface water flow that caused the oil to drift out of the test section and stick to the tank walls, the wind was simply a complicating factor. At sea, the effect of wind, besides creating Langmuir cells and "windrows" and advecting the slick en masse, is to spread the slick out in the direction of the wind (Johanssen 1986; Elliot 1986), and this latter effect can be ignored in tank testing of this scale. The test tank, with bubbler on and no wind, can thus be viewed as a small section of the upper surface layer of the ocean being advected by wind.

As the wave generator setting increased to 60, one "deep episode" (a plunging of an oil blob significantly below the surface) occurred. The oil submerged to a depth of 12 cm and returned to the undersurface of the water in 30 s. When the wind speed was increased from 0.5 to 3 m/s and the waves increased to 80 the slick was broken up into drops ranging from 0.1 to 4 cm in diameter (Figure 7). Of these, those in the 1 to 10 mm range were dispersed throughout the water. At this point, the wave generator setting was reduced to 40; the larger drops (greater than 10 mm) accumulated within 1 cm of the undersurface of the water. Increasing the wave generator setting to 80 dispersed the drops again (Figure 8).

Run A3. This run involved an oil mixture with a density of 999 kg/m^3 and a viscosity of 6280 mPas. At the lowest wave generator setting the oil formed into cylindrical shapes that were continually overwashed by 5 mm of water and underwent a cycle of "deep episodes" that involved 60 s near the surface followed by 20-30 s submerged to depths of 5 to 10 cm (Figure 9). No appreciable change in this behaviour was observed when the wave generator was increased to 50. At a wave generator setting of 60 the oil progressively broke up into droplets in the 0.1 to 5 cm diameter range.

Figure 7 - Creation of smaller oil drops, Run A2

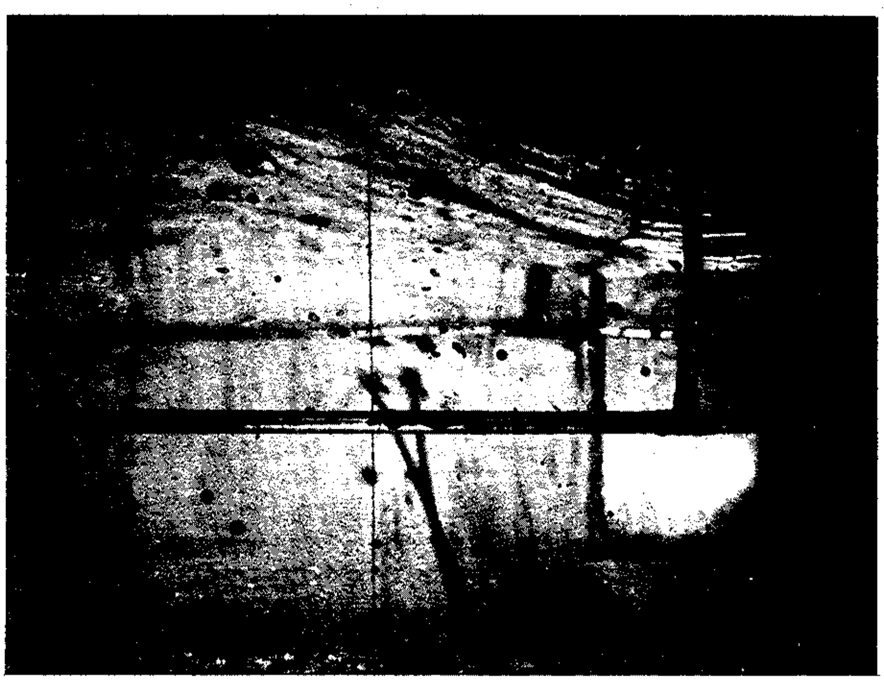


Figure 8 - Dispersion of oil drops, Run A2

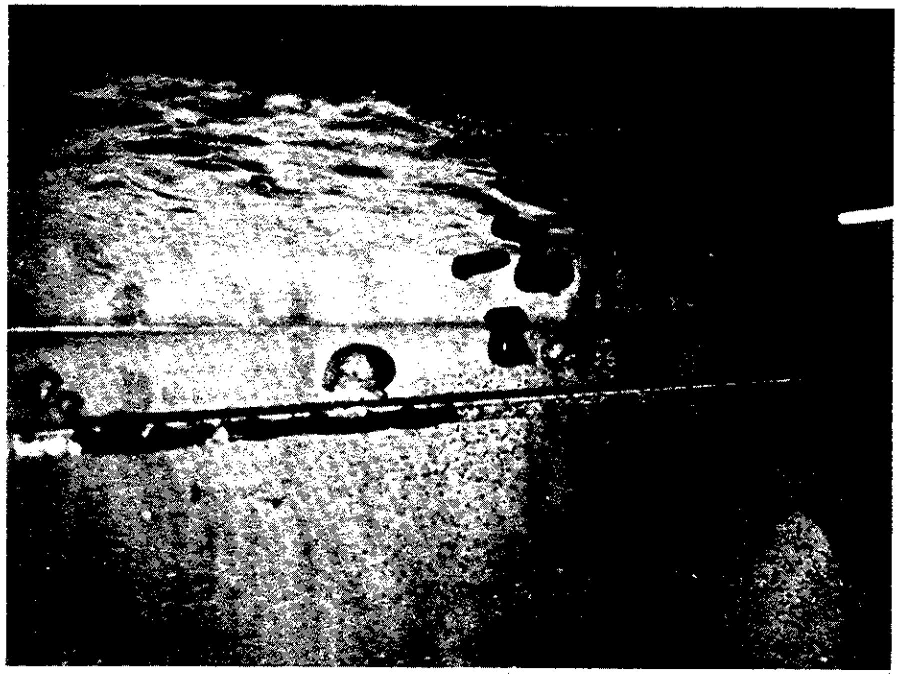


Figure 9 - Deep episodes with near-neutral buoyancy oil, Run A3

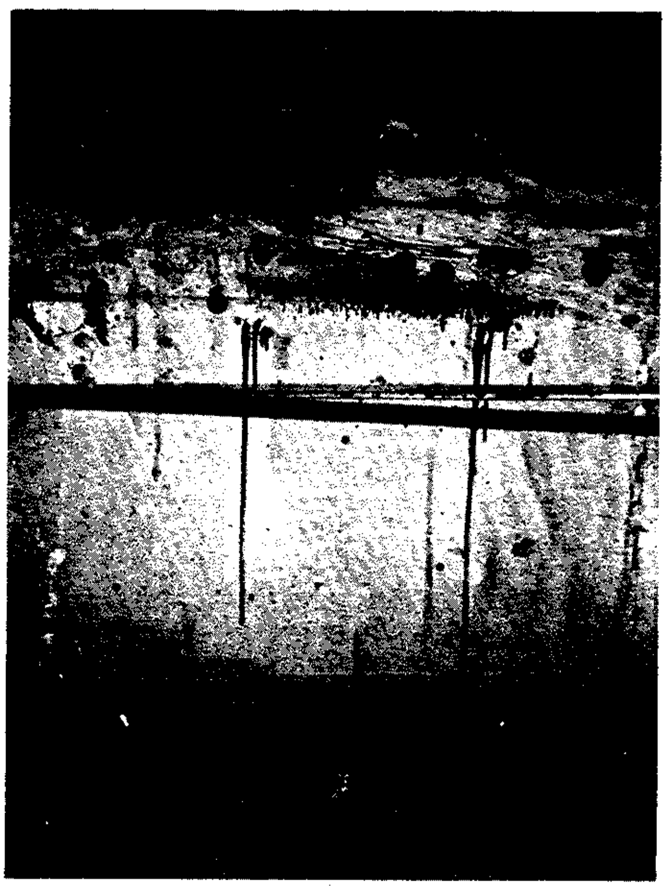


Figure 10 - Separation of small and large drops, Run A3

The drops with diameters less than 10 mm were dispersed throughout the water; those with larger diameters were found within 10 cm below the surface (Figure 10). At a wave generator setting of 80, the breaking waves fractured the larger drops and all the oil was completely dispersed.

Run A4. The density of the oil for this run was 981 kg/m^3 and the viscosity of the oil was 1480 mPas. At all the wave generator settings, the oil remained as a continuous fluid slick on the water surface (Figure 11). At a wave generator setting of 60, droplets of up to 5 mm diameter were dispersed from the slick. At a wave generator setting of 80, the oil was mostly dispersed as small (<1 mm) droplets.

Run A5. An oil mixture with a density of 958 kg/m^3 and a viscosity of 430 mPas was used in this run. As with the previous run, the surface oil remained as a continuous slick at all non-breaking wave generator settings. As the generator was increased to 60, some dispersion of 5 mm diameter drops was noted (Figure 12); at a wave generator setting of 80, all the oil was dispersed by breaking waves (Figure 13).

Run A6. A high density (1016 kg/m^3) high viscosity (16,300 mPas) oil mixture was used for this run. As was observed with uncut Bunker C (run A1) the oil did not sink on quiescent water. As soon as the waves were turned on (at the lowest setting of 40) the oil formed into pendant drops that slowly necked down and sank.

Run A7. This run involved an oil mixture of density 994 kg/m^3 and viscosity 2570 mPas. At the lowest wave generator setting of 40, the slicklets were overwashed by 1 mm of water (Figures 14 and 15). As the wave generator was increased to 60, the overwash depth increased to 1 to 3 cm (Figure 16) and "deep episodes" to 5 to 10 cm for about 20 s began. At a wave generator setting of 80 (breaking waves), the oil was broken up into drops 0.1 to 5 cm in diameter that were dispersed (Figure 17).

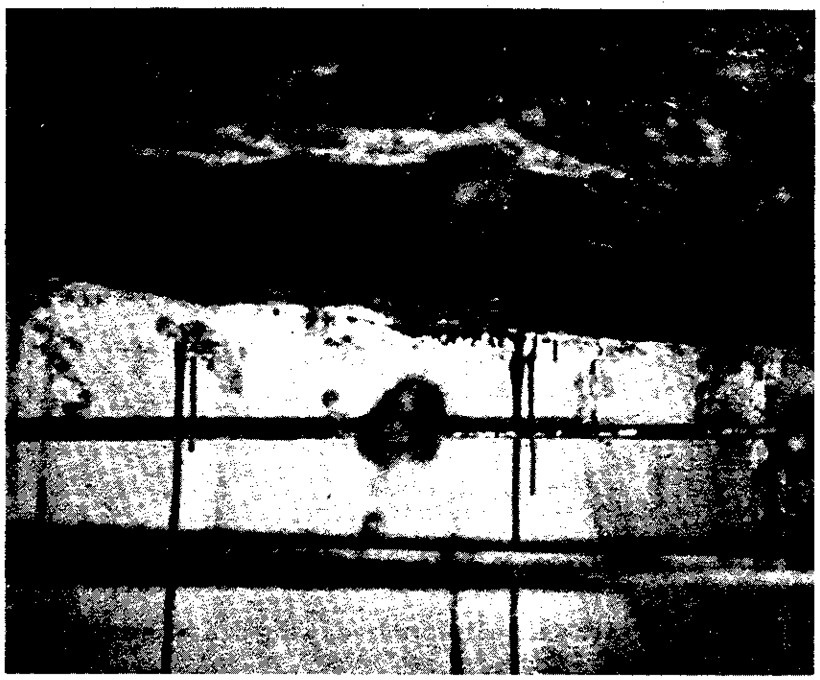


Figure 11 - Continuous slick, Run A4

Figure 12 - Continuous slick, Run A5

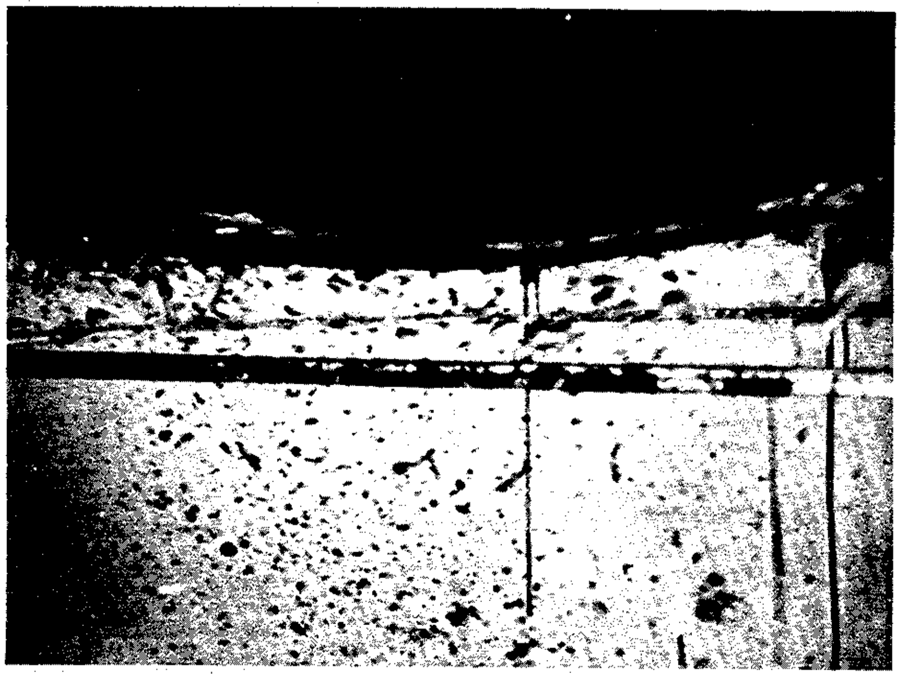


Figure 13 - Dispersion in breaking waves, Run A5

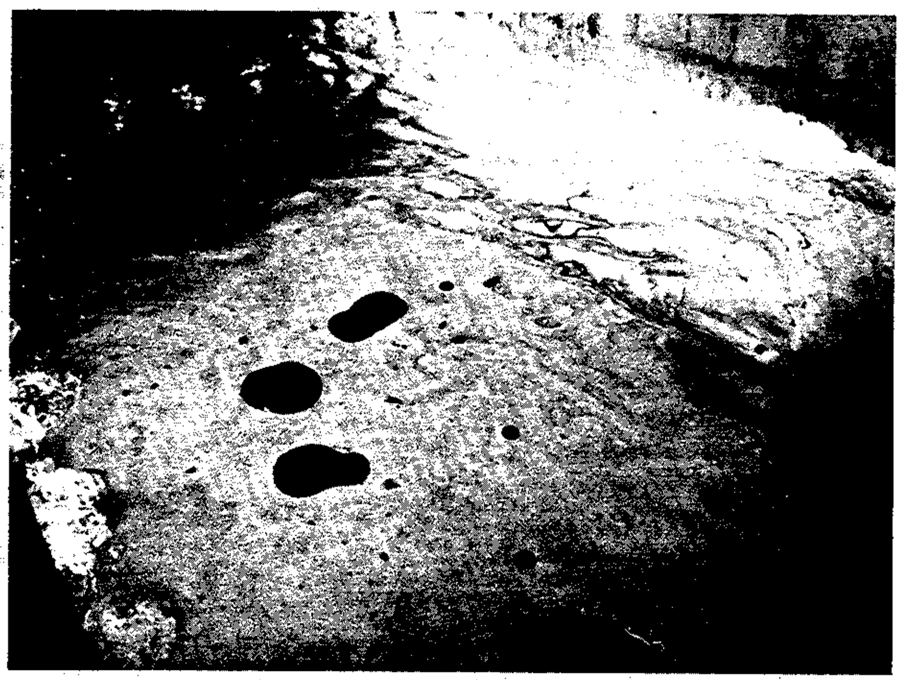


Figure 14 - Surface view of overwashed oil, Run A7

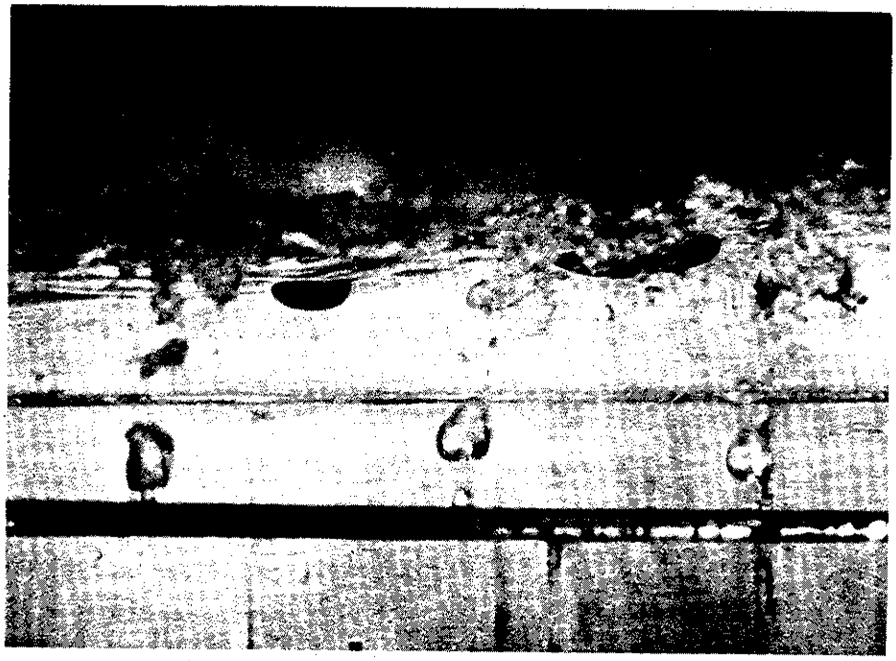


Figure 15 - Side view of overwashed oil, Run A7

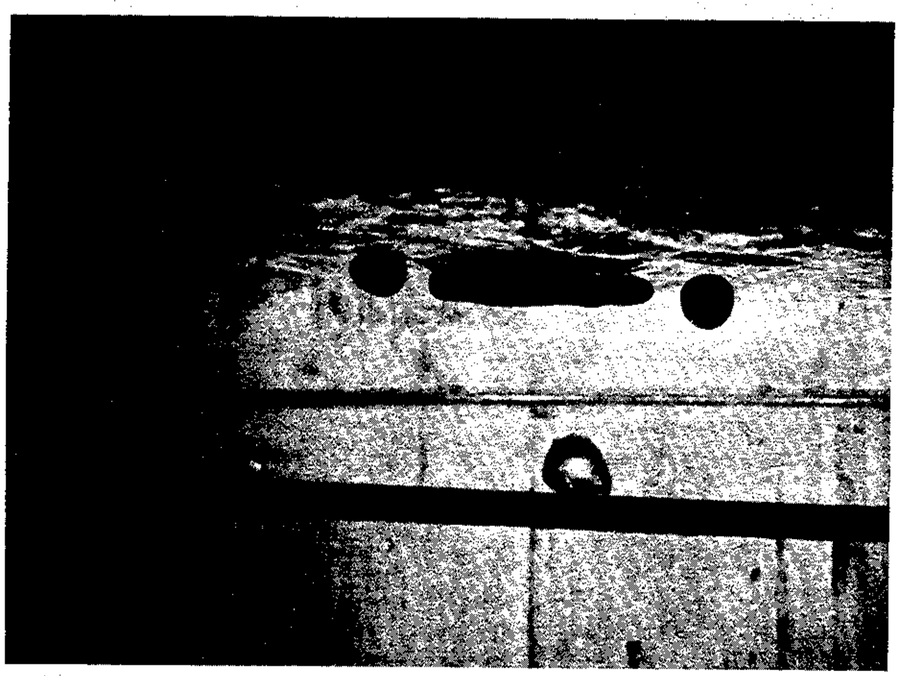


Figure 16 - Increased overwash at higher wave setting, Run A7

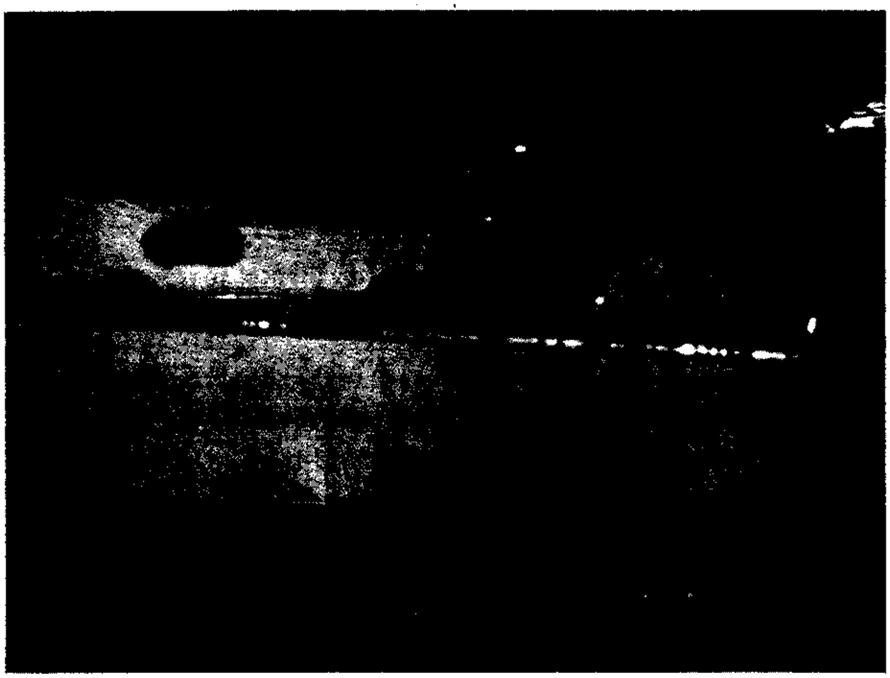


Figure 17 - Break-up and dispersion of oil in breaking waves, Run A7

Figure 18 - Surface view of partially overwashed emulsion mats, Run A8

Run A8. An emulsion of 71% salt water and J-34 crude with a density of 980 kg/m^3 and a viscosity of 842,000 mPas was used in this run. At the lowest wave generator setting the oil was slowly overwashed by 1.5 mm of water; after 4 minutes only the periphery was overwashed (Figure 18), after 7 minutes the entire slicklets were overwashed. After 18 minutes the oil had been thickened from 5 to 10-20 mm (Figure 19). At a wave generator setting of 50, the slicklets began a "manta ray" like motion with the ends rising and falling with the passing waves. The slicklets were still only overwashed with 1 to 5 mm of water. When the wave generator was increased to 80, the oil was broken up by the breaking waves with deep episodes to 5 cm for about 30 s taking place frequently. A small amount of the oil was dispersed as smaller (1-10 mm) drops (Figure 20). The wave generator was reduced to a setting of 40 at this point; all the blobs resurfaced rapidly.

Run A9. An emulsion of density 999 kg/m^3 and viscosity 591,000 mPas was used in this run. The oil on the quiescent water surface was in the form of very thick (2-5 cm) slicklets (Figure 21). At wave generator settings of 40 and 50, the slicklets were rapidly and completely overwashed by 1 to 5 mm of water (Figure 22). At a wave generator setting of 60, the overwash depth increased to 1 to 2 cm and "deep episodes" to 10 cm for about 20 s occurred. At a wave generator setting of 80, the deep episodes became more frequent, lasted for a long time and went to depths of 20 to 30 cm (Figure 23). Very little dispersion occurred, even in the breaking waves. When the wave generator setting was reduced to 40, all the blobs returned to within 1 to 5 mm of the surface within 1 to 2 minutes (Figure 24).

Run A10. This final series of tests involved an emulsion with a density of 990 kg/m^3 and a viscosity of 666,000 mPas. At a wave generator setting of 40, in six minutes the slicklets were completely overwashed by 1 mm of water. As the wave generator setting was increased to 60, some "deep episodes" to 5 cm for very short times occurred. At a setting of 80, the breaking waves caused the slicklets to fracture into slightly smaller blobs

Figure 19 - Side view of completely overwashed emulsion mats, Run A8

Figure 20 - Breakup of emulsion in breaking waves, Run A8

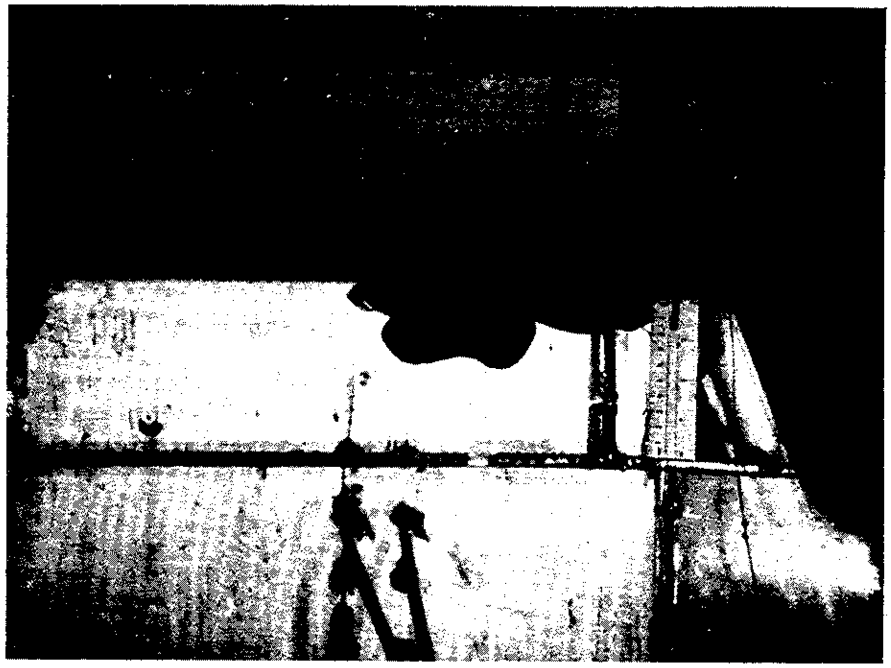


Figure 21 - Pre-test emulsion mats, Run A9

Figure 22 - Overwashed emulsion mats, Run A9

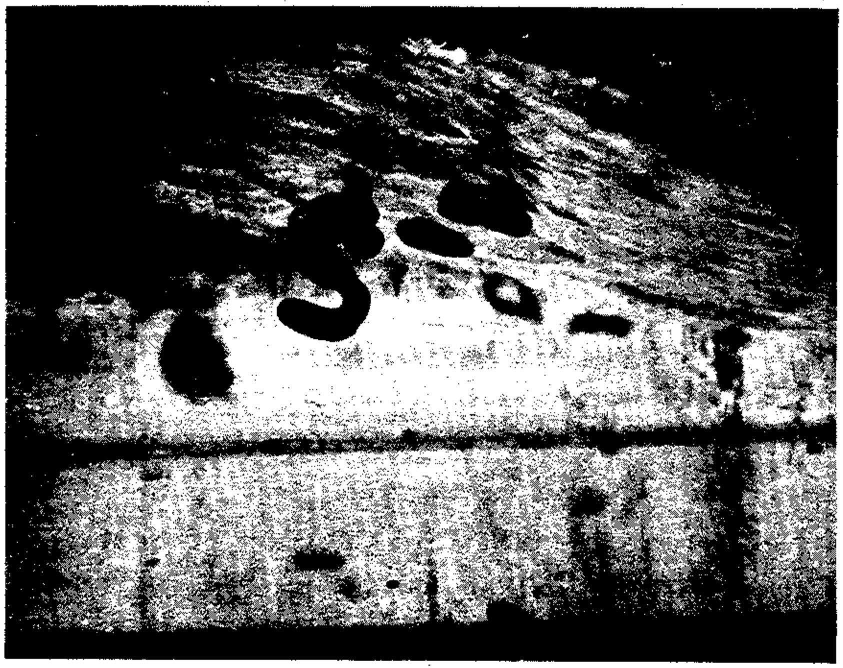


Figure 23 - Deep episodes, Run A9

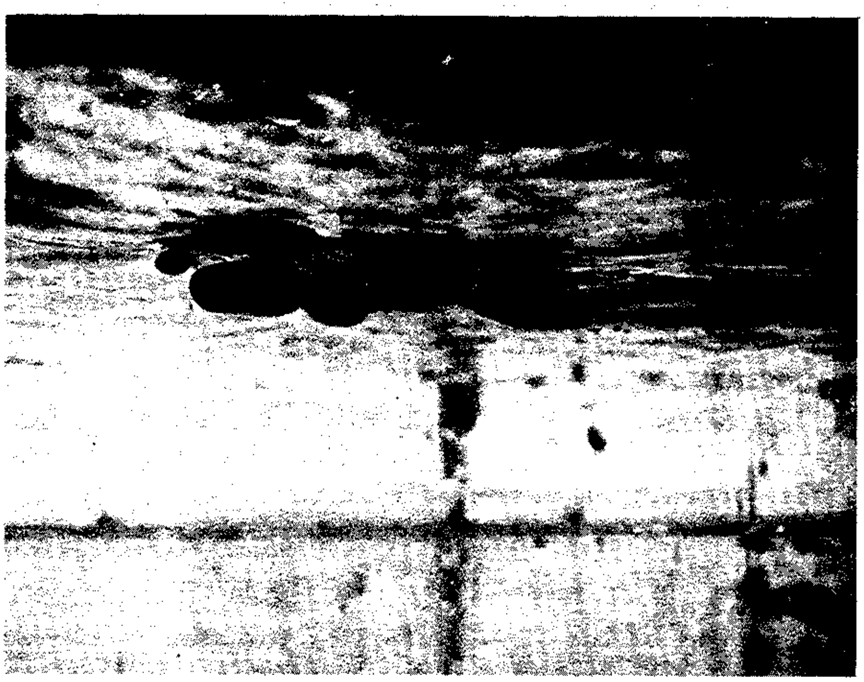


Figure 24 - Resurfaced emulsion blobs, Run A9

and created frequent "deep episodes" to 5 to 10 cm; very little dispersion occurred (Figure 25). When the wave generator setting was reduced to 40, all the blobs resurfaced rapidly to within 1 mm of the surface (Figure 26).

3.2.1 Summary of General Behaviour

Based on the observations from the test runs it seems that three criteria must be met for overwashing and transient submergence (i.e., "deep episodes") to occur: firstly, and most obviously, the oil must have a density close to that of the water; secondly the oil must be viscous enough to break into slicklets or blobs that have the potential to be overwashed; and finally the energy in the waves must be sufficient to actually submerge these high density oil forms. The data from these and other tests are next used to develop equations that mathematically describe these processes.

3.3 DEVELOPMENT OF PROCESS EQUATIONS

Two groups of process equations have been developed: one to predict whether a given oil in a given sea state will break into slicklets and blobs and to estimate the size of these oil forms; and the second to predict the depth of overwash, maximum transient submergence depth and the distribution of temporarily submerged oil with depth.

3.3.1 Slick Breakage

Raj (1977) presents a mathematical model in which the maximum normal tensile stress in a slick (caused by the stretching and thinning action as waves pass beneath) is compared with the molecular cohesion of the slick to determine whether or not a given slick in a given sea state will break into slicklets. In his analysis, he uses the surface tension (i.e., oil/air interfacial tension) of the slick divided by the slick thickness as a measure of slick cohesion. Unfortunately, this implies that thicker slicks

Figure 25 - Emulsion blob deep episodes in breaking waves, Run A10

Figure 26 - Resurfaced emulsion blobs, Run A10

are easier to break than thinner slicks, a result that contradicts intuition and experience. Rather than divide surface tension by slick thickness, it is more appropriate to divide by a measure of the length of surface that the force is acting along; in this case wave amplitude seems reasonable. Starting from Raj's (1977) equation, modified to replace thickness with amplitude, which gives as the slick breakage criteria:

1) $C_1 \sigma / a < 2 \mu_o \Gamma max$

where σ = surface tension (N/m)
a = wave amplitude (m)
μ_o = oil viscosity (Pas)
C_1 = a constant
Γmax = maximum strain rate in a slick subjected to a sinusoidal wave (s^{-1})

and substituting:

2) $\Gamma max = W/2(A^2-1)^{1/2}$

where W = wave frequency (rad/s)
A = steepness parameter
$= \dfrac{1 + (\pi s)^2}{2 \pi s}$
s = wave steepness
$= 2a/\lambda$
λ = wavelength (m)

and, for deep-water gravity waves:

3) $W = (2 \pi (1-s) g / \lambda)^{1/2}$

where g = acceleration of gravity (m/s^2)

yields, for the oil viscosity limit for slick breakage:

4) $\mu_o > C_1 (\sigma^2(A^2-1)/ \pi a s(1-s)g)^{1/2}$

Examination of the test data shows that oils with viscosities less than about 1500 mPas (Runs A4 and A5) did not form into slicklets or blobs at any non-breaking wave condition while oils with viscosities higher than 2500 mPas did. The value of C_1 is thus tentatively set at 30. This gives a minimum oil viscosity for breakage of 2000 mPas at a wave generator setting of 60. As the waves begin to break, A approaches 1 thus predicting, correctly, that even the lowest viscosity oils will fracture, though the mechanism of fracture in breaking waves is not stretching and thinning of the slick.

Equation 4 predicts that, for a given continuous slick on the sea, breakage will occur as the oil weathers (thus increasing the viscosity), as the wave amplitude increases (for a given wave steepness), as the wave steepness increases (for a given amplitude) or as the surface tension of the oil decreases. For the purposes of this study (because of the difficulties encountered in measuring the interfacial tension of viscous oils) the surface tension of any oil is assumed constant at 30 mN/m.

3.3.2 Slicklet/Blob Size

Raj (1977) gives an equation for the strain rate a slick undergoes as sinusoidal waves pass beneath it:

5) $\Gamma(\theta) = W \sin \theta/2(A-\cos\theta)$

where θ = Kx
= angular displacement
x = distance from origin (m)
K = wave number (m^{-1})
= $2 \pi / \lambda$

using the breakage criteria given in equation 1:

6) $C_2 \sigma / a = \mu_o W \sin \theta / (A - \cos \theta)$

or

$\sin \theta / (A - \cos \theta) = C_2 \sigma / aW \mu_o$

in order to simplify, for x between 0 and $\lambda/8$, θ is between 0 and $\pi/4$. In this range $\sin \theta \approx \theta$ and $\cos \theta \approx 1$ or:

7) $\dfrac{\theta}{(A-1)} \approx C_2 \sigma / aW \mu_o$

or

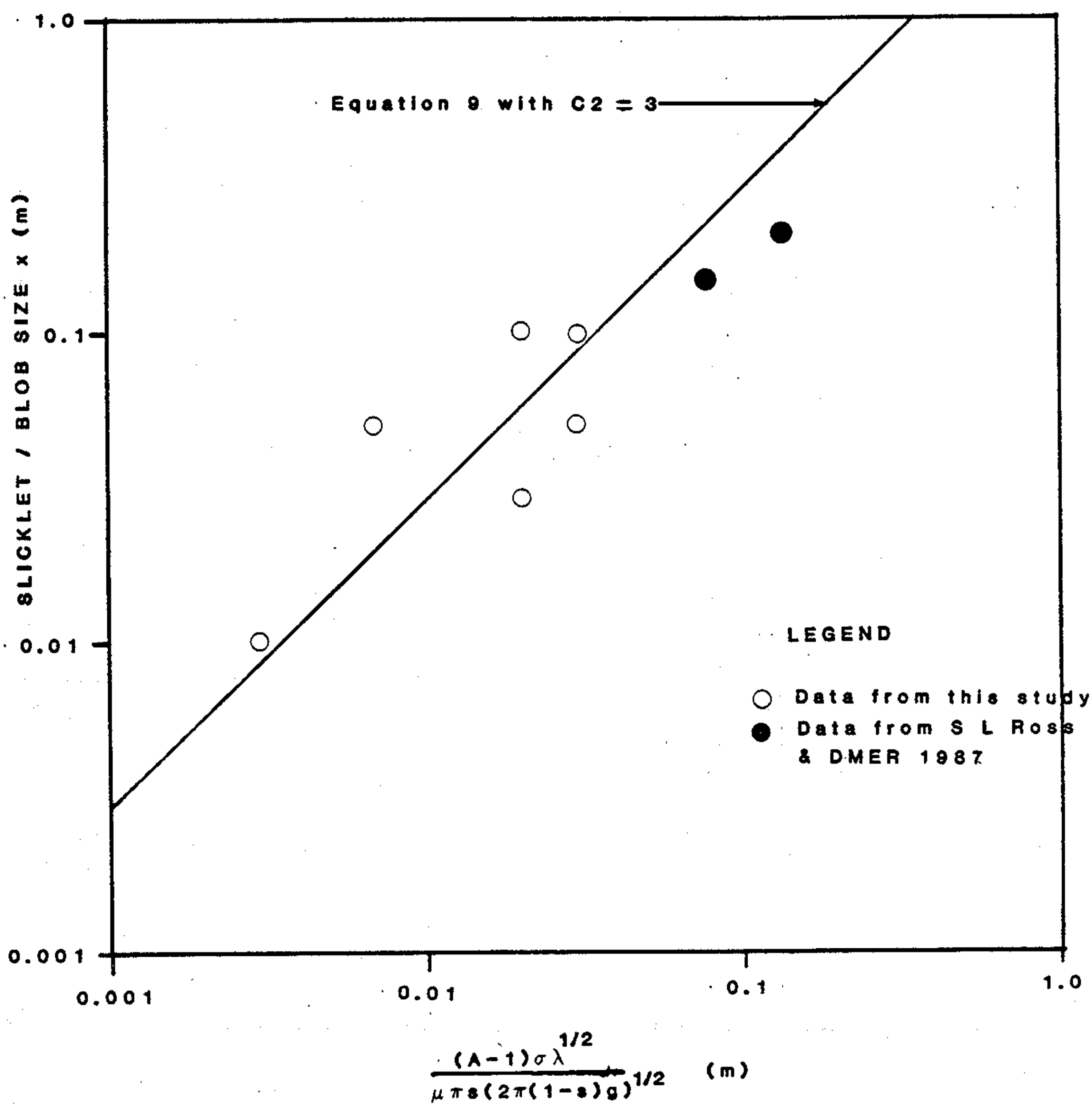
8) $\theta \approx (A-1) C_2 \sigma / aW \mu_o$

substituting for θ and W (for deep-water gravity waves) yields

9) $x = C_2 (A-1) \sigma \lambda^{1/2} / \mu_o \pi s (2\pi (1-s) g)^{1/2}$

Figure 27 shows a plot of the data for those runs where slick breakage occurred at wave settings less than 80 (breaking waves make A approach 1), and equation 9 with $C_2 = 3$. Also shown are data from two runs with waxy crude oils (S.L. Ross and DMER 1987). Although the fit is far from perfect, the equation predicts the trends in the data and can be used to obtain order of magnitude estimates of slicklet and blob sizes. Equation 9 is not suitable for use with very viscous oils or emulsions since these behave almost as solids. The viscosity cutoff,above which equation 9 is no longer valid, was arbitrarily chosen as 50,000 mPas.

FIGURE 27 - EXPERIMENTAL SLICK BREAKAGE DATA



3.3.3 Overwash Depth

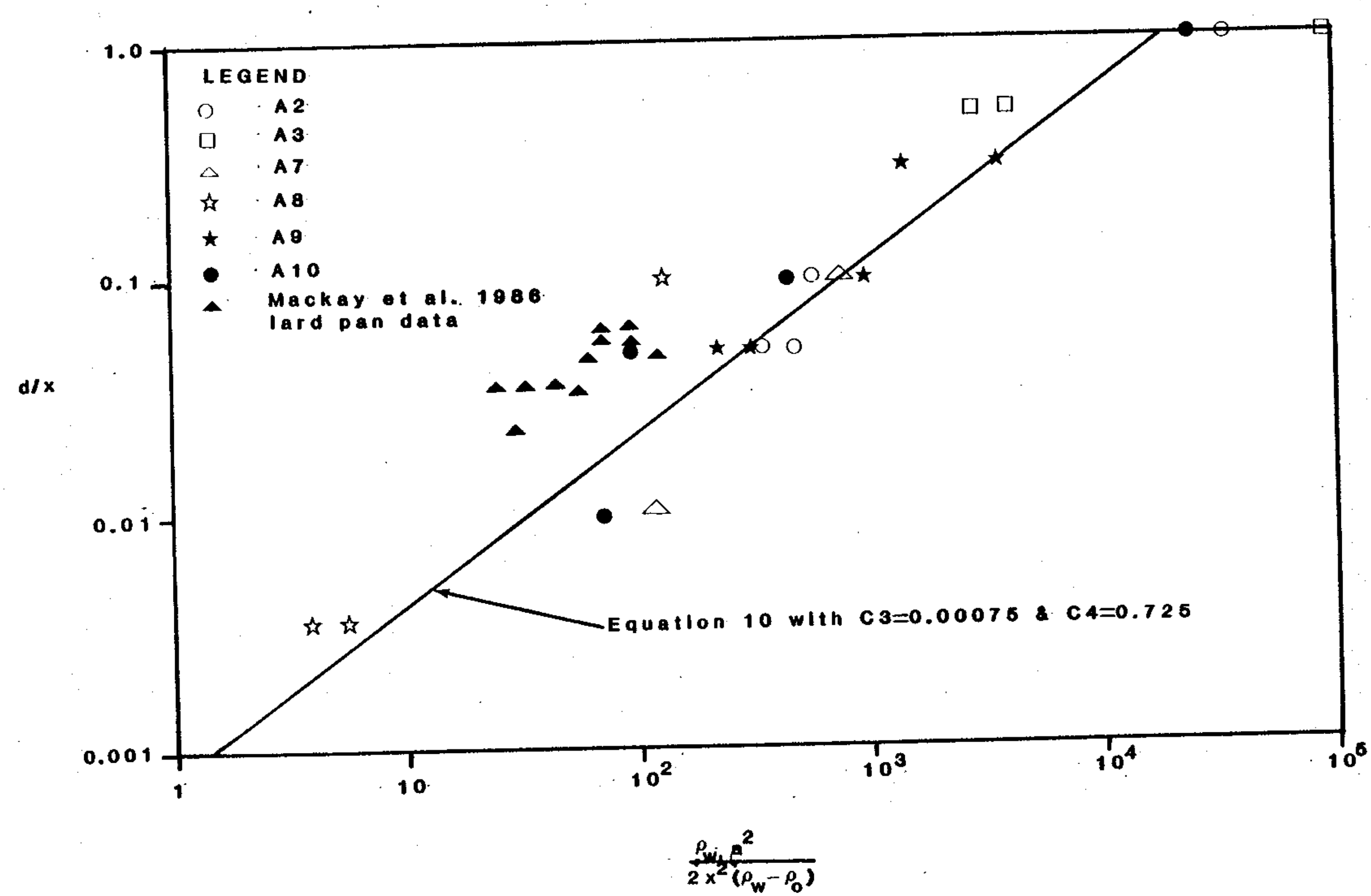
Overwashing is defined as the minimum thickness of water on top of slicklets and blobs in a wave field. By dimensional analysis, including wave energy, oil-water density difference, slicklet/blob size and gravity as factors that influence overwashing in non-breaking waves, it was determined that:

10) $$\frac{d}{x} = C_3(\rho_w\, a^2/2x^2(\rho_w - \rho_o))^{C4}$$

where d = overwash depth (m)
ρ_w = water density (kg/m^3)
ρ_o = oil density (kg/m^3)

Figure 28 shows a plot of the data points for those runs that involved overwashing (i.e., those in which the oil was in the form of slicklets or blobs). Also shown is equation 10 with $C_3 = 7.5 \times 10^{-4}$ and $C_4 = 0.725$ and the data of Mackay et al. (1986) for lard pans. The scatter is due to imprecision in measuring both the submergence depth and slicklet or blob size in a moving system. It should be noted that slicklets in a previous study with viscous, waxy oils were not overwashed due to their low density relative to the oil used in this study. This is dealt with in the modelling section later by setting the minimum overwash depth as 1 mm (i.e., if equation 10 predicts an overwash less than 1 mm, it is designated as not being overwashed). This cutoff was selected on the basis of observations of runs A8 and A10 during which the slicklets were slowly overwashed. The portions of the slick overwashed by water were covered by a least 1 mm; the above water portions were dry; no areas were covered by less than 1 mm of water. As well, conventional aerial remote sensors for oil spills will not detect oil with more than 1 mm of water overwashing the slick (Fingas 1987).

FIGURE 28 - EXPERIMENTAL OVERWASH DATA



Equation 10 is intuitively correct in that the overwash depth increases with increasing wave height and oil density and decreases with increasing slicklet size.

3.3.4 Maximum Transient Submergence Depth

Maximum transient submergence depth is defined as the deepest that a buoyant slicklet or blob was propelled during a "deep episode". By dimensional analysis it was found that submergence depth could be correlated with the same factors as overwash depth, i.e.,:

11) $$\frac{d^1}{x} = C_5(\rho_w a^2/2x^2(\rho_w - \rho_o))^{C6}$$

where d^1 = maximum transient submergence depth (m)

Figure 29 shows the data from the test runs and equation 11 with $C_5 = 2.9 \times 10^{-2}$ and $C_6 = 0.615$. Also shown are the data of Mackay et al. (1986) for lard pans and the range of data for plastic spheres, both under wave conditions.

Equation 11 is consistent with the correlations presented by Mackay et al. (1986):

for lard pans,

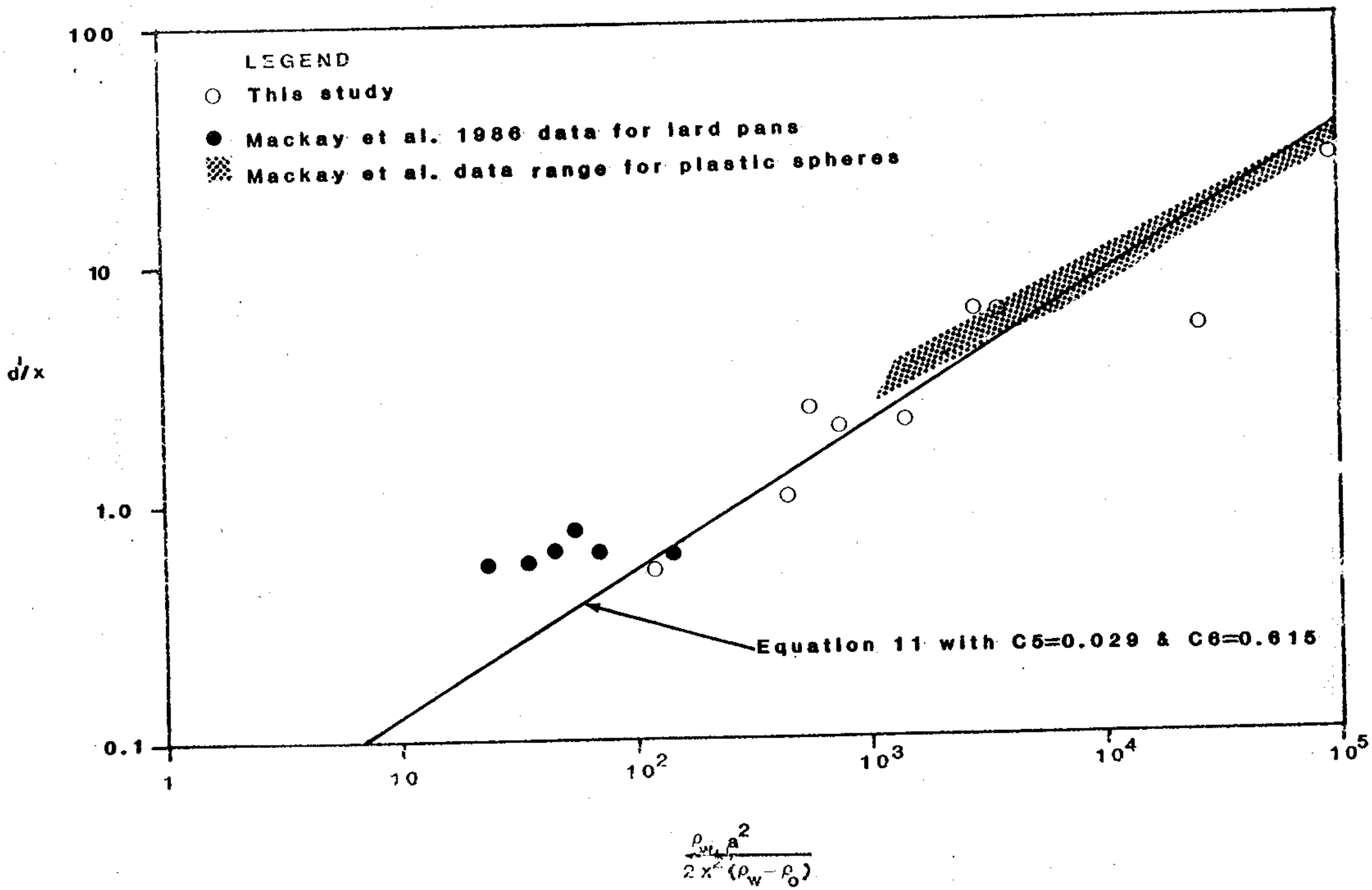
12) $$d^1 = 0.009U^2/(\rho_w - \rho_o)^{0.8}$$

with d in cm, the wind speed U in m/s and densities in g/cm^3

and, for plastic spheres,

13) $$d^1 = 0.2/(\rho_w - \rho_o)$$

FIGURE 29 - EXPERIMENTAL MAXIMUM SUBMERGENCE DATA



3.3.5 Depth Distribution of Oil

The probability of an oil form being below a certain depth d (or alternatively, for a slick containing many slicklets or blobs, the fraction of the oil below depth d) can be expressed as (Mackay et al. 1986).

14) $P = \exp - (d/c)^b$

where P = probability
c = characteristic length (m)
b = a constant

Assuming that equation 10 (overwash depth) represents the depth below which the oil spends 95% of its time and equation 11 (maximum transient submergence depth) represents the depth above which the oil spends 95% of its time, substituting into equation 14 yields:

15) $0.95 = \exp - (7.5 \times 10^{-4} x(\rho_w \ a^2/2x^2(\rho_w - \rho_o)^{0.725}/c)^b$

and

16) $0.05 = \exp - (2.9 \times 10^{-2} \times (\rho_w \ a^2/2x^2(\rho_w - \rho_o)^{0.615}/c)^b$

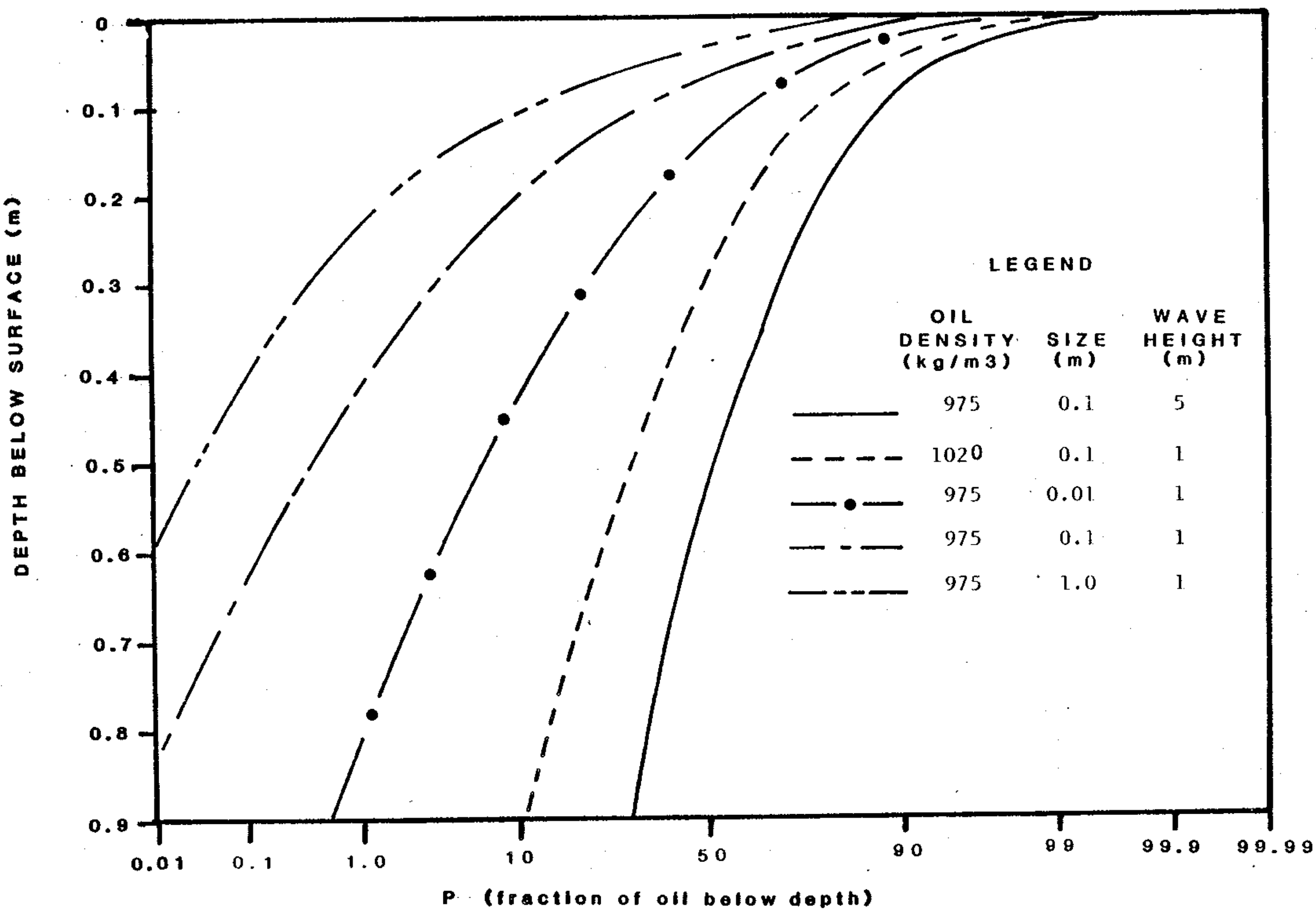
Solving for c and b gives the probability distribution as:

17) $P = \exp - (91.5d/x(\rho_w \ a^2/2x^2(\rho_w - \rho_o))^{0.64467})$

with b = 1 within the accuracy of the data.

Example distributions for various oil and wave conditions are shown on Figure 30. At a constant oil buoyancy and wave height the effect of increasing slicklet or blob size is to shift the distribution towards the surface; at constant wave height and slicklet size the effect of reducing oil buoyancy is to shift the distribution deeper; at constant buoyancy and slicklet size the effect of increasing wave height is also to shift the distribution deeper.

FIGURE 30 – EXAMPLE CALCULATED OIL DEPTH DISTRIBUTIONS



4. INCORPORATION INTO AN OIL BEHAVIOUR COMPUTER MODEL

4.1 THE OIL FATE MODEL

The purpose of the incorporation of the process equations into a computer model was to allow predictions of submergence behaviour as oil slicks weather, spread and emulsify with time. The approach taken in this study to predict transient oil submergence at sea was to modify an existing oil fate and behaviour model. The main features of this model are presented prior to discussing the modifications. A program listing in Fortran is given in Appendix 1.

The model is based primarily on work performed at the University of Toronto over the past decade; oil spreading is based on the model of Mackay et al. (1979) which utilizes the thick/thin approach; oil evaporation is based on the evaporative exposure approach of Stiver and Mackay (1983), and subsequent oil property changes are determined using the approach of Tebeau et al. (1983); sea state (i.e., wind speed) and oil properties are used to calculate natural dispersion (after S.L. Ross 1984) and emulsification (after Mackay et al. 1979, modified to include a delay until the particular oil weathers to an emulsifiable state). A routine has also been included to assess chemical dispersion effectiveness (S.L. Ross 1987), though this was not used for this study.

In its present form, the model requires a fairly large number of oil property inputs to be used to its full potential. Much of this information is presently available in oil property catalogues published by Environment Canada (S.L. Ross 1985; Bobra and Chung 1986) for many Canadian oils. Work is also underway at the University of Toronto (S.L. Ross and DMER 1987) to develop a technique to fully quantify oil property changes with evaporation using only a simple distillation procedure.

4.2 MODIFICATIONS TO PREDICT SUBMERGENCE

4.2.1 Data Input and Initialization

The primary modifications to this part of the program included changes to input the sea parameters of swell height (a^1) and wavelength (λ^1), surface water density (ρ_S) and the depth to the pycnocline (d^{11}). In the initialization portion of the program, wave properties are calculated from wind speed (U = m/s at 10 m height), using the following equations given by Raj (1977) for a fully developed sea:

18) RMS+ waveheight = $a^* = 7.83 \times 10^{-3}\ U^2$ (m)

19) average wavelength = $\lambda = 1.06\ U^2$ (m)

20) average waveheight = $a = 1.77\ a^*$

21) wave steepness = $S = 2\ a/\lambda$

22) swell steepness = $S^1 = 2\ a^1/\ \lambda^1$

The program then checks which is steeper, the swell or the waves and uses the amplitude and wavelength of the steeper to calculate the steepness parameter A using the expression given for equation 2.

4.2.2 Mainline

The first step in the mainline calculation program is to check if the oil or emulsion density exceeds that of seawater (1025 kg/m^3); if so the oil sinks and the program terminates. If the oil or emulsion density lies

+ sea state index = a* in feet

between that of the surface water and 1025 kg/m^3 the oil sinks to the pycnocline depth covering an area equal to the thick slick area calculated for that iteration and the program is terminated.

If the oil density is less than that of the seawater, the program checks to see if the oil or emulsion viscosity exceeds the minimum for slick breakage given by equation 4. If not the program spreads and weathers the oil for one iteration and returns to the beginning; if the oil is viscous enough to break, the size of the slicklets/blobs is calculated using equation 9.

Next the program calculates the overwash depth for the slicklets/blobs using equation 10 (with rms waveheight); if the overwash depth is less than 1 mm the program spreads and weathers the oil for one iteration and returns to the beginning. If the overwash exceeds 1 mm, the program calculates the maximum transient submergence depth from equation 11 and compares it to the pycnocline depth; the lesser of the two is used. The program then calculates the fractions of the oil between the surface and 10 cm deep, between 10 cm deep and 1 m deep, and deeper than 1 m below the surface. The fractions are adjusted if the pycnocline is less than a metre below the surface.

Finally, if the oil is overwashed, the program stops spreading the thick portion of the slick (i.e., the submerged portion); the thin sheen continues to exist on the surface, fed by the submerged slicklets/blobs. This latter feature is based on anecdotal accounts of actual spills rather than laboratory test data. Evaporation, emulsification and natural dispersion of the thick slick are assumed to continue as if the oil were on the surface. These oil fate processes for submerged oil need to be addressed in future studies.

4.3 MODELLING RESULTS

Figure 31 shows the predicted behaviour and properties for a crude oil with an initial density of 900 kg/m^3 and initial viscosity of 25 mPas that emulsifies when spilled on water with a surface density of 1020 kg/m^3 in a 5 m/s wind with no swell. Over the time period graphed the oil spreads, evaporates, emulsifies and naturally disperses until after 3 1/2 days about 50% of the original 1000 m^3 spill is left. Figure 32 shows the same spill in the same conditions except that a very steep (s=0.06) swell has been added. In this case, after 18 hours the emulsion becomes viscous enough (2900 mPas) and dense enough (994 kg/m^3) to be broken into slicklets about 2.5 m in diameter overwashed by 2 cm of water. The predicted maximum transient submergence depth is about 0.5 m. Slicklet size decreases slowly with time; both overwash and maximum submergence depth increase with time.

Figure 33 gives the predicted results if the initial oil density is increased to 990 kg/m^3, the surface water density is reduced to 1015 kg/m^3 and all other parameters remain the same. In this situation, the oil breaks up into emulsion slicklets at the same time as the previous case (Figure 32) but the initial overwash and maximum transient submergence depth are about a factor of ten greater. After two days exposure, the emulsion density exceeds that of the surface water and the oil sinks to the pycnocline at a depth of 10 m.

Figure 34 shows the predicted behaviour of the Bunker C spilled by the Kurdistan. Oil property information was taken from C-CORE (1980); environmental information at the time of the spill was obtained from Vandermeulen and Buckley (1985). In the high seas at the time of the incident, the model predicts that blobs in the size range of 0.6 m would be overwashed by about 10 cm of water. The maximum transient submergence depth is predicted to have been about 2 m. Very little weathering of the Bunker C is predicted thus the oil would survive for long times. These predictions are broadly consistent with the anecdotal accounts given by Reimer (1981).

FIGURE 31 - PREDICTED BEHAVIOUR OF 900kg/m3 CRUDE OIL SPILL IN A 5 m/s WIND AND NO SWELL

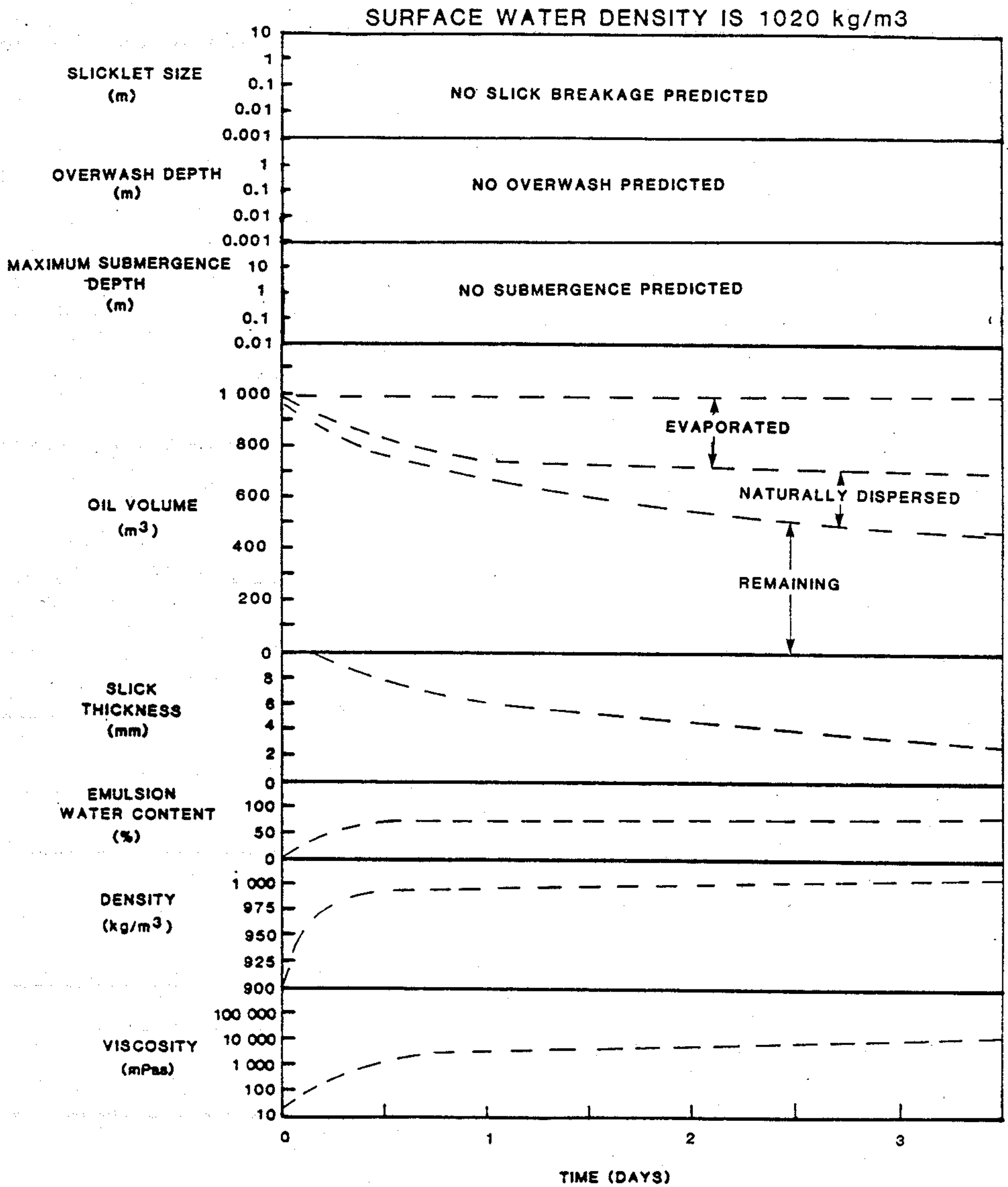


FIGURE 32 - PREDICTED BEHAVIOUR OF 900kg/m3 CRUDE OIL SPILL IN A 5 m/s WIND AND 3m SWELL

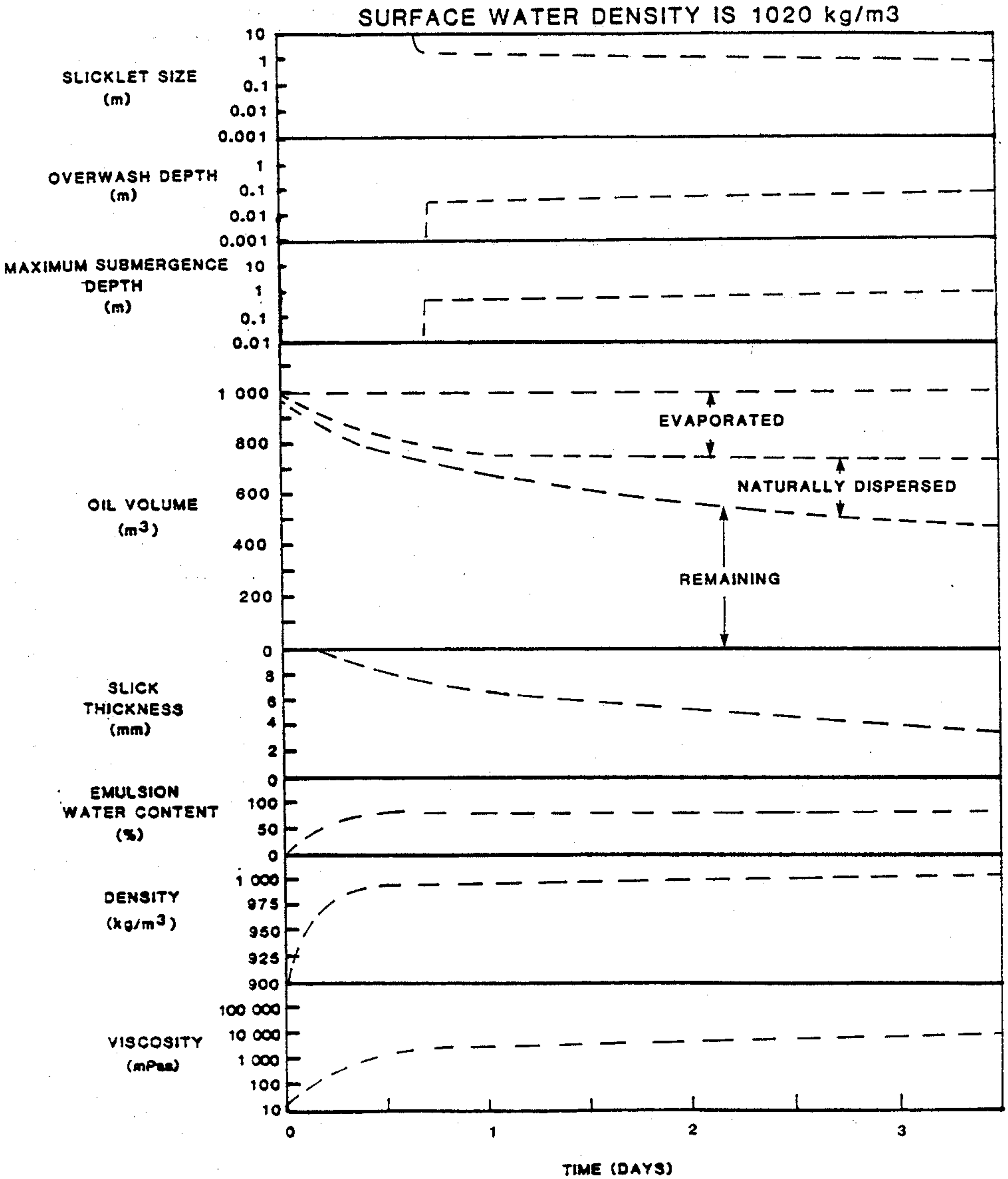


FIGURE 33 - PREDICTED BEHAVIOUR OF 990kg/m3 CRUDE OIL SPILL IN A 5 m/s WIND AND 3m SWELL

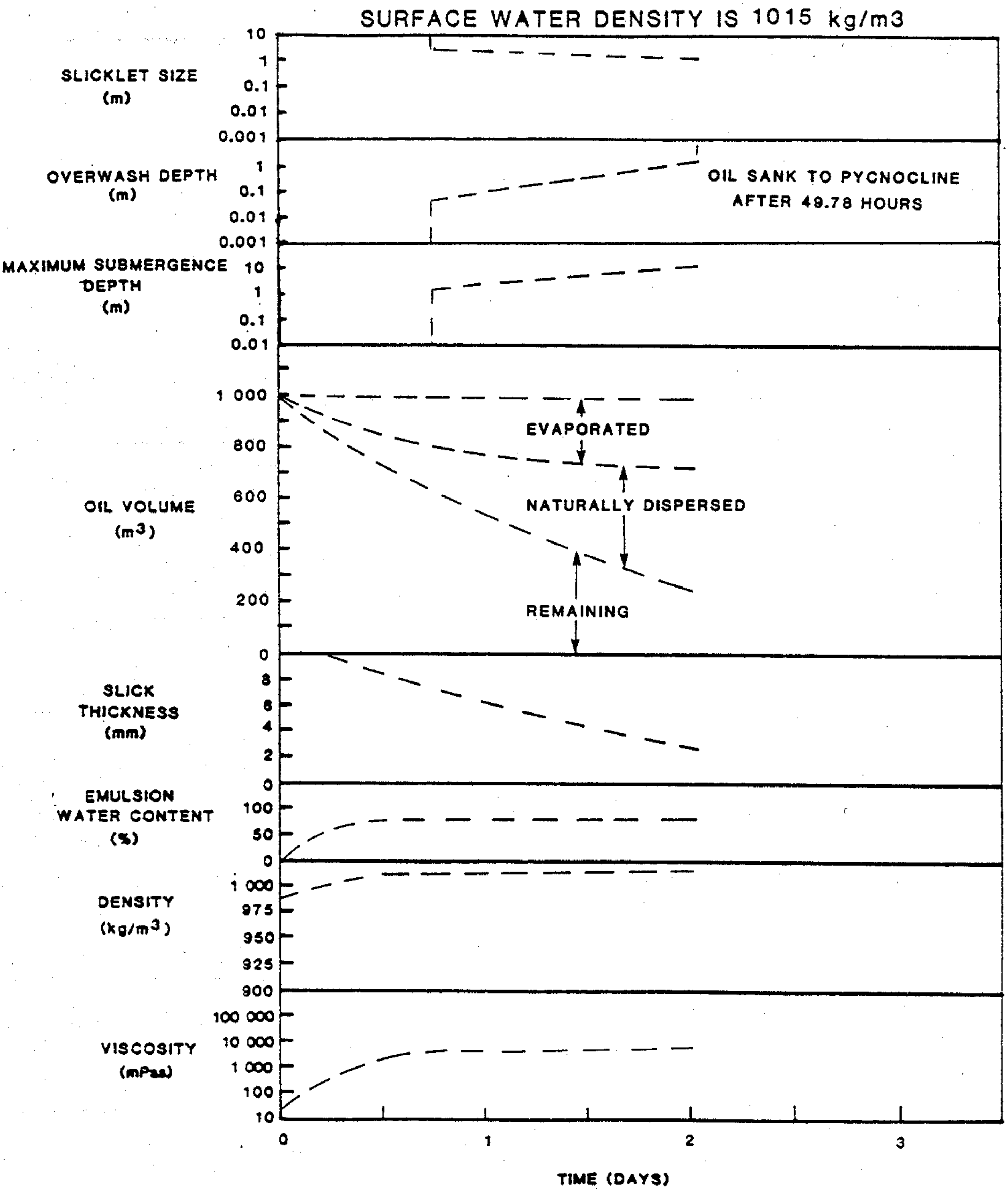
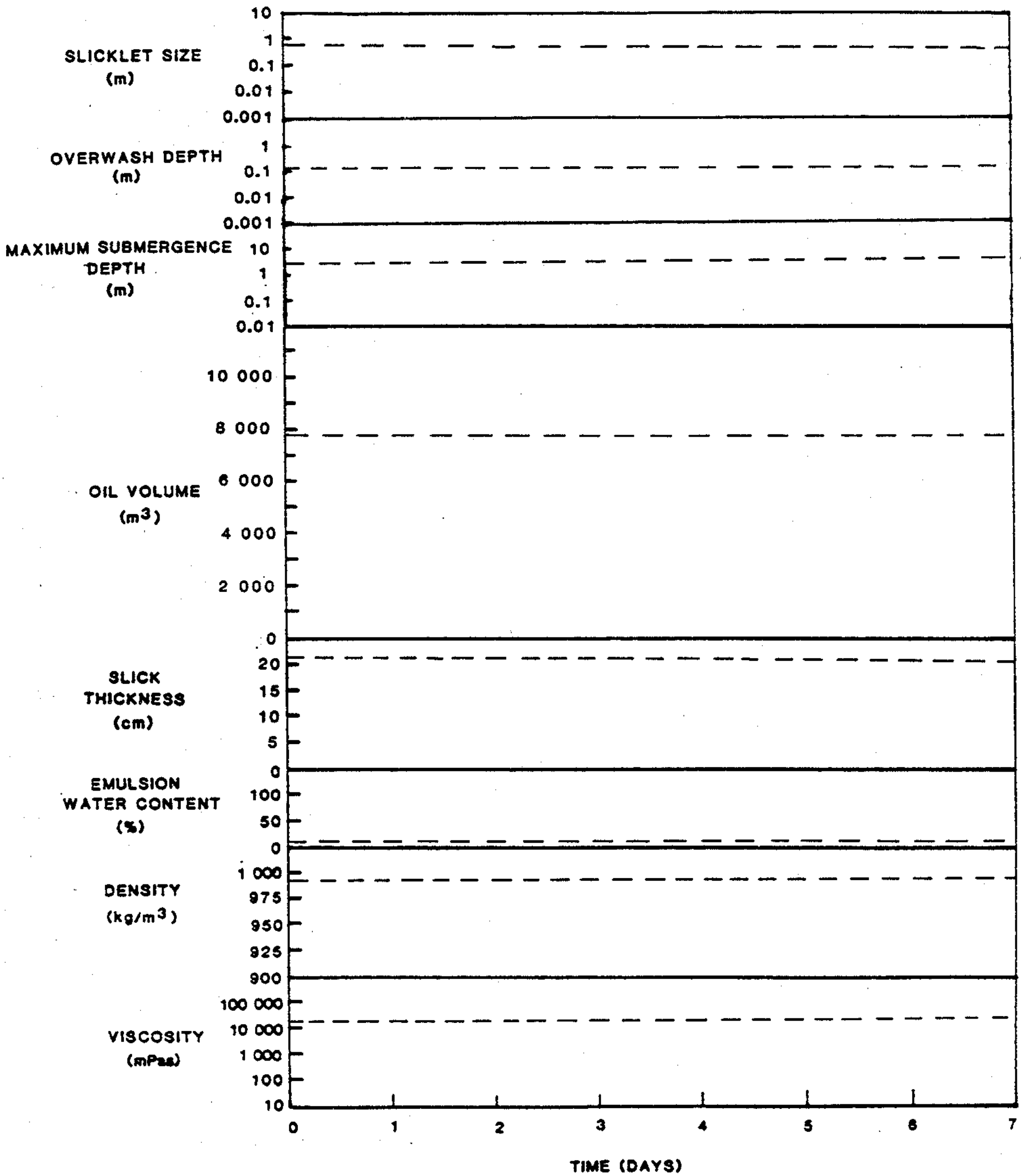


FIGURE 34 - PREDICTED BEHAVIOUR OF KURDISTAN BUNKER C SPILL

SURFACE WATER DENSITY= 1020 kg/m3 ,WIND =10 m/s ,SWELL = 7 m



4.4 SIMPLIFIED NOMOGRAPH

In order to obtain quick estimates for emergency response purposes, the process equations have been simplified by substituting the predictive equations for rms waveheight, average waveheight and average wavelength for a fully developed sea into equation 9 to predict slicklet blob size and equation 10 to predict overwash depth, yielding for non-emulsified oils:

$$23)\quad d(cm) = 4.6 \times 10^{-5}\ U^{2.45}\ \mu_o^{0.45}/((\rho_w - \rho_o)/\rho_w)^{0.725}$$

and for emulsified oils (which behave as solids and are not "broken" by waves)

$$24)\quad d(cm) = 4.0 \times 10^{-5}\ U^{2.9}/((\rho_w - \rho_o)/\rho_w))^{0.725}\ x^{0.45}$$

The ratio of overwash depth to maximum transient submergence depth (equation 11 divided by equation 10) is approximately 40 since $C_6 - C_4$ is very small.

Figure 35 shows a nomograph for fully developed sea conditions with a surface water density of 1025 kg/m^3 (35 ppt) based on equation 23 for a range of residual fuel oils. Figure 36 shows a nomograph based on equation 24 for the submergence of emulsion mats/blobs of various sizes.

The residual oil properties used were heavy Bunker C (from this study) medium Bunker C (from data on the Kurdistan spill), light Bunker C (from Bobra and Chung 1986), and heavy Bunker B, or No. 5 fuel oil (from Bobra and Chung 1986). Predictions are given for 1000 kg/m^3 emulsion with mat/blob sizes of 1, 0.1 and 0.01 m.

FIGURE 35 - OVERWASH / SUBMERGENCE NOMOGRAPH
RESIDUAL FUEL OILS

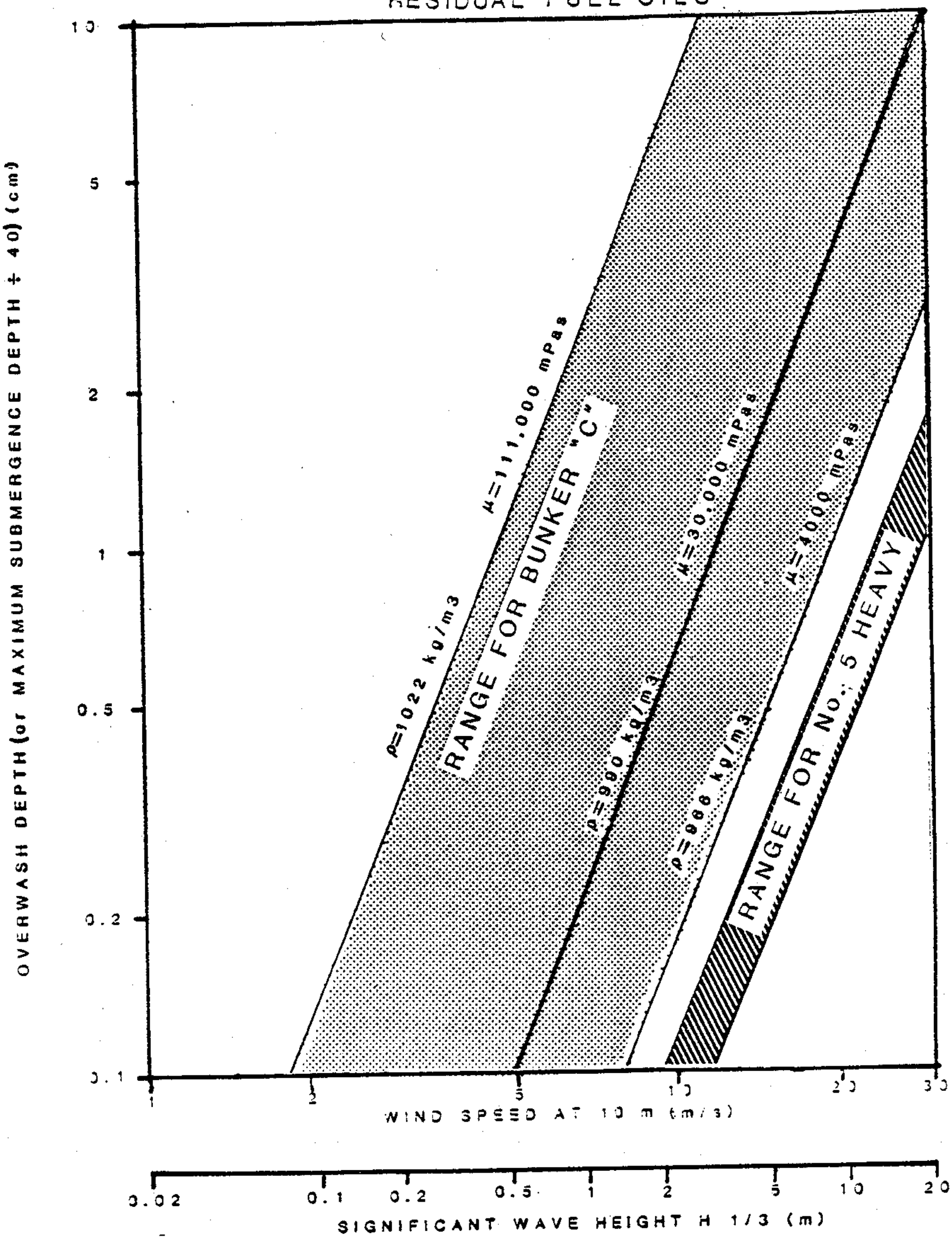
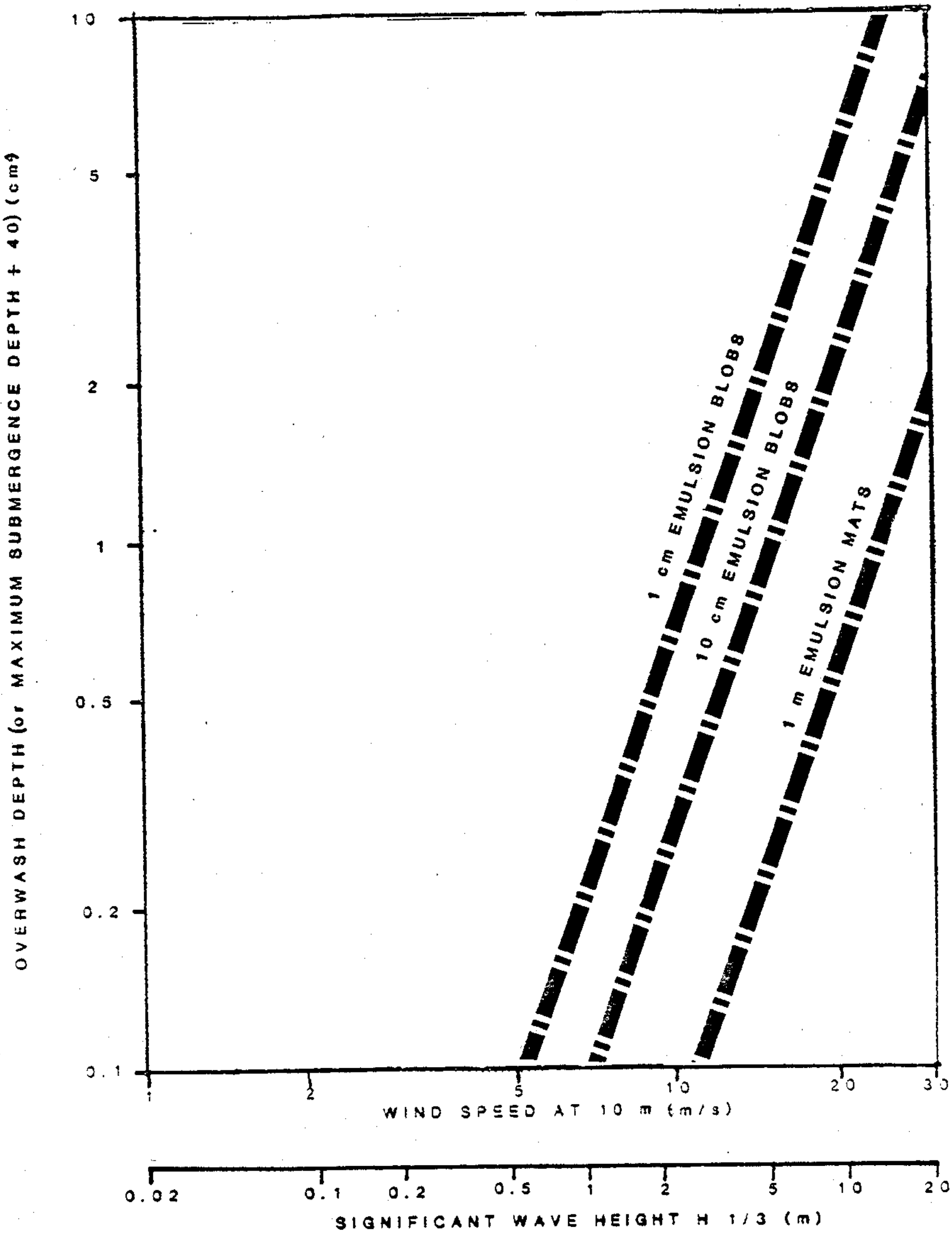


FIGURE 36 - OVERWASH / SUBMERGENCE NOMOGRAPH
EMULSIONS (ρ = 1000 kg/m3)



If oil property information is available during a spill response, equation 23 or 24 can be used to obtain better estimates. If surface salinities are lowered, oil weathering or emulsification is expected to take place or other complicating factors exist, the computer model should be used with the best available input data.

5. CONCLUSIONS AND RECOMMENDATIONS

The overwashing and transient submergence of oil spills on water depends primarily on the buoyancy of the oil or emulsion, the viscosity of the emulsion and the sea state. A necessary condition for overwashing or transient submergence is that the oil be of sufficiently high viscosity so that it can be broken into discrete slicklets or blobs by wave action. Once this occurs, the degree of overwashing and transient submergence is controlled by the size and buoyancy of the slicklets or blobs and the prevailing sea state. For non-emulsified oils the size of the slicklets or blobs is determined by sea conditions and the surface tension and viscosity of the oil. Emulsions, due to their enormous viscosities, behave almost as solids; emulsion mat or blob sizes are possibly only a function of sea conditions but this is unknown.

Based on theory and wind/wave tank test results, process equations incorporating oil properties and sea conditions have been developed to predict: whether or not a particular oil slick will break up into slicklets or blobs, the size of the resultant slicklets and blobs, whether or not they are overwashed by water and to what extent, the maximum transient submergence depth of the slicklets and blobs and their distribution as a function of depth. These process equations have been incorporated into an oil spill fate and behaviour computer model that calculates oil spreading, evaporation, emulsification and natural dispersion to allow state-of-the-art predictions of transient submergence. The process equations were also simplified to provide quick estimates for residual fuel oil spills and a range of emulsion mat sizes.

It is recommended that the models be updated as further field data become available, that a study on the processes of evaporation, emulsification and natural dispersion of submerged oil be undertaken, and that the results of this study be incorporated into an oil spill trajectory model for submerged oil.

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APPENDIX 1

Computer Program Listings

```
      PROGRAM OILFATE
      REAL R(30),IOILD,IOILV,IASOL,IOILFP,IOWINT,IOAINT,IOILPP,MSDPTH
      INTEGER OUTI
      COMMON /GEN/ TSTEP,TCOUNT,ZTHICK,ZTHIN,WINDS,OILD,OILV,TTK,TTKE
      COMMON /VAP/ AIRT,ASTMA,ASTMT
      IN=1
      IO=2
      PI=3.14159
C***
      CALL DATAIN(R)
C***
      WRITE (IN,10)
10    FORMAT(10X,'DATA ACCESSED CORRECTLY',/)
C
C**   INITIALIZE VARIABLES
C
      OILVT=R(1)
      SDUR=R(2)
      WINDS=R(3)
      AIRT=R(4)
      WATERT=R(5)
      IOILD=R(6)
      SDTEMP=R(7)
      DC1=R(8)
      DC2=R(9)
      IOILV=R(10)
      SVTEMP=R(11)
      VC1=R(12)
      VC2=R(13)
      IOILPP=R(14)
      PPC=R(15)
      SWELLH=R(16)
      SWELLL=R(17)
      SURDEN=R(18)
      PYCDEP=R(19)
      IOWINT=R(20)
      OWINTC=R(21)
      IOAINT=R(22)
      OAINTC=R(23)
      ASTMT=R(24)
      ASTMA=R(25)
      OUTI=IFIX(R(26))
      TTKE=R(27)
      TDISA=R(28)*3600.
      ROWINT=R(29)
      DDUR=R(30)*3600.
C
C
      TSTEP=100.
      ZTHICK=0.02
      ZTHIN=0.000001
C
      DOILV=OILVT/(SDUR/TSTEP)
```

```
      OILVL=DOILV
      TCOUNT=TSTEP
C
      SFACT=1.0
      IDIS=0
      ISTOP=0.0
      TTK=0.0
      FEVTK=0.0
      FEVTNI=0.3
      FEVTN=FEVTNI
      FDTK=0.0
      FDTN=0.0
      WW=0.0
      EMULD=IOILD
      EMULV=IOILV
      SIGMA=.07-IOAINT-IOWINT
      TVEV=0.0
      TVEVTK=0.0
      TVEVTN=0.0
      TVDTK=0.0
      TVDTN=0.0
      VDTN=0.0
      TVDIS=0.0
      OILV=IOILV
      OWINT=IOWINT
      OILD=IOILD
      TNOILV=IOILV
C
      IOUT=1
      ITIME=0
C
C     INITIAL SLICK CONDITION
C
      ATK=OILVL/(ZTHICK+8.*ZTHIN)
      ATN=8.*ATK
      VTK=ZTHICK*ATK
      VTN=ZTHIN*ATN
      VTOTN=VTN
C
C WAVE CONDITIONS
C
      WINDSS=WINDS*WINDS
      ASTAR=7.83E-03*WINDSS
      AVEWL=1.06*WINDSS
      AVEWH=1.77*ASTAR
      WSTEEP=2*AVEWH/AVEWL
      SSTEEP=2*SWELLH/SWELLL
      IF(SSTEEP.LT.WSTEEP) GO TO 41
      WSTEEP=SSTEEP
      AVEWH=SWELLH
      ASTAR=SWELLH
      AVEWL=SWELLL
41    A=(1+(PI*WSTEEP)**2)/(2*PI*WSTEEP)
C
C
```

```
C
      WRITE(IN,11)
11    FORMAT(10X,'RUN INITIALIZED CORRECTLY',/)
C
1     IF(TCOUNT.GE.TDISA.AND.TCOUNT.LT.(TDISA+DDUR))GO TO 888
      IF(IDIS.EQ.1)OWINT=POWINT
      SFACT=1.0
      GO TO 1199
888   IF(IDIS.EQ.0)POWINT=OWINT
      IDIS=1
      OWINT=ROWINT
      SFACT=2.0
1199  CALL EVAP(FEVTK,FEVTN,DFEVTK,DFEVTN)
      CALL SPREAD(ATK,ATN,ADIFF,SIGMA,OILPP,WATERT,SFACT,IDIS)
      CALL EMULS(WW,EMULD,EMULV,SURDEN)
      CALL DISPRS(FDTK,FDTN,OWINT,EMULD,EMULV,TNOILV)
C
      IF(EMULD.GE.1025.OR.EMULD.GE.SURDEN)GO TO 999
C
C
C     CALCULATE NEW OIL PROPERTIES
C
      OILD=IOILD+DC1*FEVTK-DC2*(WATERT-SDTEMP)
      OILV=IOILV*EXP(VC1*FEVTK)*EXP(VC2*((1/WATERT)-(1/SVTEMP)))
      TNOILV=IOILV*EXP(VC1*0.5)*EXP(VC2*((1/WATERT)-(1/SVTEMP)))
      OILPP=IOILPP*(1+PPC*FEVTK)
      OWINT=IOWINT*(1+OWINTC*FEVTK)
      OAINT=IOAINT*(1+OAINTC*FEVTK)
      IF(SFACT.EQ.2.0)OWINT=ROWINT
      SIGMA=.07-OAINT-OWINT
C
C     CALCULATE NEW SLICK CHARACTERISTICS
C
C     OIL SINKING ROUTINE
C
      UOB=30.*SQRT(OAINT*OAINT*(A*A-1)/(PI*AVEWH*WSTEEP*(1-WSTEEP)*
     +9.81))*1000.
      IF(UOB.GT.EMULV)GO TO 51
     DBLOB=3*(A-1)*OAINT*SQRT(AVEWL)/(EMULV*PI*WSTEEP*SQRT(2*PI*(1-WSTE
     +EP)*9.81))*1000.
      F=SURDEN*ASTAR*ASTAR/(2*DBLOB*DBLOB*(SURDEN-EMULD))
      OWDPTH=7.5E-04*DBLOB*F**0.725
      IF(OWDPTH.LT.0.001)GO TO 51
      OILPP=WATERT
      SIGMA=0.0
      MSDPTH=2.94E-02*DBLOB*F**0.615
      IF(MSDPTH.GT.PYCDEP)MSDPTH=PYCDEP
C
C  FRACTION OF OIL BETWEEN SURFACE AND 10 CM
C
      FTEN=1-EXP(-9.15/(DBLOB*F**0.64467))
      IF(PYCDEP.GT.0.1)GO TO 61
      FTEN=1.0
      GO TO 51
C
```

```
C  FRACTION BETWEEN 10CM AND 1 METRE .
C
61      FMETRE=1-EXP(-91.5/(DBLOB*F**0.64467))-FTEN
        IF(PYCDEP.GT.1.) GO TO 71
        FMETRE=1-FTEN
        GO TO 51
C
C  FRACTION BELOW 1 METRE
C
71      FDEEP=1-FTEN-FMETRE
        IF (FDEEP.LT.0.01)FDEEP=0.0
C
C
51      ESTOP=FEVTK
        IF(FEVTK.GT.FEVTNI)ESTOP=FEVTNI
        VEVTN=DFEVTN*VTN+VTOTN*(FEVTNI-ESTOP)
        VDTN=FDTN*VTN
        SUM=VEVTN+VDTN
        IF(SUM.LT.VTN)GO TO 161
        FACT=VTN/SUM
        VDTN=VDTN*FACT
        VEVTN=VEVTN*FACT
161     VEVTK=DFEVTK*VTK
        TVEV=TVEV+VEVTK+VEVTN
        TVEVTK=TVEVTK+VEVTK
        TVEVTN=TVEVTN+VEVTN
        VDTK=FDTK*VTK
        TVDIS=TVDIS+VDTK+VDTN
        TVDTK=TVDTK+VDTK
        TVDTN=TVDTN+VDTN
        VTOTN=ATN*ZTHIN-VTN
        VTK=VTK-VEVTK-VDTK-VTOTN
        VTN=VTN+VTOTN-(VDTN+VEVTN)
        ZTHICK=VTK/ATK
        VOLUM=VTK+VTN
        AREA=ATK+ATN
C
        IF(VTK .LT. .0001*OILVT.OR.VOLUM/AREA.LT.1.E-06) ISTOP=1
        IF (ISTOP.EQ.1)GO TO 36
C
        IOUT=IOUT+1
        TCOUNT=TCOUNT+TSTEP
C
        IF(TCOUNT .GT. SDUR) GO TO 2
C
        VTK=VTK+DOILV
        ZTHICK=ZTHICK+DOILV/ATK

C
2       IF(IOUT .NE. 36*OUTI) GO TO 1
36      ITIME=ITIME+1
        IOUT=1
        IF(MOD(ITIME,2))35,35,25
25      WRITE(IO,111)
111     FORMAT('1')
```

```
35        IJTIME=ITIME*OUTI
          IF(ISTOP.EQ.1)IJTIME=IFIX(TCOUNT/3600)
          WRITE(IO,100)IJTIME
100       FORMAT(2X,'TIME (HRS.) - ',I4,/)
          WRITE(IO,200)
200       FORMAT(13X,' AREA  THICKNESS   VOLUME   TF EVAP  TotVolEvap
     +F DIS   TotVolDis')
          WRITE(IO,300)
300       FORMAT('+',13X,'____  _________  ______  _______  __________
     +  ___________')
          WRITE(IO,400)ATK,ZTHICK,VTK,FEVTK,TVEVTK,FDTK,TVDTK
400       FORMAT(2X,'THICK',3X,F10.0,1X,F7.6,2X,F10.3,2X,F6.4,2X,F10.3,2X,
     +F6.4,2X,F10.3)
          WRITE(IO,500)ATN,ZTHIN,VTN,DFEVTN,TVEVTN,FDTN,TVDTN
500       FORMAT(2X,'THIN',4X,F10.0,1X,F7.6,2X,F10.3,2X,F6.4,2X,F10.3,2X,
     +F6.4,2X,F10.3)
          WRITE(IO,600)
600       FORMAT('+',10X,'__________',10X,'__________',10X,'__________',
     +10X,'__________')
          AREA=ATK+ATN
          VOLUM=VTK+VTN
          WRITE(IO,700)AREA,VOLUM,TVEV,TVDIS
700       FORMAT(10X,F10.0,10X,F10.3,10X,F10.3,10X,F10.3)
          WRITE(IO,800)ADIFF
800       FORMAT(' BY OKUBO-',F10.0,/)
          WRITE(IO,900)
900       FORMAT(32X,'OIL PROPERTIES',/,32X,'--------------',/)
          WRITE(IO,101)
101    FORMAT(13X,' DENSITY',4X,'VISCOSITY',3X,'WATER CONTENT',3X,'THICKN
     +ESS')
          WRITE(IO,202)
202       FORMAT('+',12X,' _______',4X,'_________',3X,'_____________',3X,'
     +_________')
          EMTHK=ZTHICK/(1.0-WW)
          WRITE(IO,303)OILD,OILV,ZTHICK,EMULD,EMULV,WW,EMTHK
303       FORMAT(1X,'OIL',6X,':',2(F10.0,3X),16X,F7.6,/,' EMULSION :',2(F1
     +0.0,3X),4X,F6.4,6X,F7.6,/)
          WRITE(IO,404)
404       FORMAT(4X,'BLOB D',5X,'OW DEPTH',5X,'MS DEPTH',3X,'F TEN CM',2X
     +,'F 10-METRE',5X,'F DEEP',5X,'THETA')
          WRITE(IO,505)
505       FORMAT('+',3X,'______',5X,'________',5X,'________',3X,'________
     +',2X,'__________',5X,'______',5X,'_____')
          WRITE(IO,606)DBLOB,OWDPTH,MSDPTH,FTEN,FMETRE,FDEEP,TTK
606       FORMAT(3X,F6.4,6X,F6.3,7X,F6.3,6X,F6.4,6X,F6.4,6X,F6.4,3X,F9.0,/
     +,/,/,/)
          WRITE(IO,707)
707       FORMAT(20X,'. . . . . . . . . . . . . . . . . . . . . . ',/,/,/,/)
          IF (ISTOP.EQ.1) GO TO 999
          GO TO 1
999       IF(ISTOP.EQ.1)GO TO 998
          tcount=tcount/3600.
          IF (EMULD.GT.SURDEN)WRITE(IO,901)ATK,TCOUNT
          IF(EMULD.GT.1025)WRITE(IO,902)ATK,TCOUNT
901       FORMAT(5X,'OIL HAS SANK TO PYCNOCLINE OVER AN AREA OF- ',F9.0,
```

```
     +2x,'sq. metres',2X,'AFTER ',F6.2,2X,'hours.',/)
902     FORMAT(5X,'OIL HAS SANK TO BOTTOM OVER AN AREA OF- ',F9.0,2X,
     +'sq. metres',2x,'AFTER ',F6.2,2X,'hours.',/)
998     STOP
        END
```

```
      SUBROUTINE DATAIN(R)
      REAL R(30)
      BYTE IDFN(11)
      IO=1
      IN=1
      LUN=6
C***
      DO 3 I=1,30
3     R(I)=0.0
C***
      WRITE (IO,100)
100   FORMAT(3X,'ENTER DATA FILE NAME...AAAAAAA TTT',/)
      READ (IN,101) IDFN
101   FORMAT(11A1)
C*****
      CALL OPEN (LUN,IDFN,2)
C*****
      WRITE (IO,102)
102   FORMAT (3X,'Return for NEW or INITIAL Data Entry',/,3x,'Enter *
     +666  * for Data CHANGE',/,3X,'ENTER * - 666 * TO RUN PROGRAM',/)
      READ (IN,103) IROUTE
103   FORMAT (I5)
      IF (IROUTE) 4,1,2
C***
104   FORMAT(F20.8)
113   FORMAT(30F20.8)
106   FORMAT(3X,'ENTER DESIRED VALUE FOR VARIABLE # -',I2,/)
C***
C***
1     DO 10 I=1,15
      WRITE(IO,105) (R(J),J=1,15)
      WRITE (IO,106)I
      READ(IN,104) VARI
10    WRITE(LUN,104,REC=I) VARI
C***
C***
      DO 20 I=16,30
      WRITE (IO,110) (R(J),J=16,30)
      WRITE (IO,106)I
      READ(IN,104) VARI
20    WRITE(LUN,104,REC=I) VARI
      GO TO 4
C***
2     WRITE(IO,112)
112   FORMAT (3X,'REVIEW THE FOLLOWING LIST FOR THE # OF THE VARIABLE
     + TO BE CHANGED',/)
C**
      DO 50 J=1,30
50    READ(LUN,113,REC=J) R(J)
      WRITE (IO,105) (R(J),J=1,15)
      WRITE(IO,111)
```

```
111     FORMAT('0','PRESS RETURN TO DISPLAY REMAINING VARIABLES',/)
        PAUSE
        WRITE (IO,110) (R(J),J=16,30)
C***
        WRITE (IO,107)
107     FORMAT(3X,'ENTER # OF VARIABLE FOR CHANGE',/)
        READ (IN,108)IV
108     FORMAT(I2)
        IF (IV.EQ.99) GO TO 4
        WRITE(IO,109)IV
109     FORMAT(3X,'ENTER NEW VALUE FOR - ',I2,/)
        READ(IN,104)VALUE
        WRITE(LUN,104,REC=IV) VALUE
C**
        GO TO 2
C**
4       DO 2000 J=1,30
2000    READ(LUN,200,REC=J) R(J)
200     FORMAT(30F20.8)
        WRITE(2,105)(R(J),J=1,15)
        WRITE(2,110)(R(J),J=16,30)
C**
105     FORMAT(3X,'* 1 *  Oil Volume [Cu M] - ',F20.8,/,
     +3x,'* 2 *  Duration of Spill [Sec] - ',F20.8,/,
     +3x,'* 3 *  Wind Speed [M/S @ 10 M] - ',F20.8,/,
     +3x,'* 4 *  Air Temperature [K] - ',F20.8,/,
     +3x,'* 5 *  Water Temperature [K] - ',F20.8,/,
     +3x,'* 6 *  Fresh Oil Density [Kg/cu M] - ',F20.8,/,
     +3x,'* 7 *  Standard Density Temperature [K] - ',F20.8,/,
     +3x,'* 8 *  Density Constant  [DC1] - ',F20.8,/,
     +3x,'* 9 *  Density Constant  [DC2] - ',F20.8,/,
     +3x,'* 10 *  Fresh Oil Viscosity [mPas] - ',F20.8,/,
     +3x,'* 11 *  Standard Viscosity Temperature [K] - ',F20.8,/,
     +3x,'* 12 *  Viscosity Constant [VC1] - ',F20.8,/,
     +3x,'* 13 *  Viscosity Constant [VC2] - ',F20.8,/,
     +3x,'* 14 *  Fresh Oil Pour Point [K] - ',F20.8,/,
     +3x,'* 15 *  Pour Point Constant [PPC] - ',F20.8,/,
     +,/,3X,'* 99 *     CHANGES COMPLETED  ',/)
110      FORMAT(3X,'* 16 *  Swell Height [m] - ',F20.8,/,
     +3x,'* 17 *  Swell Length [m] - ',F20.8,/,
     +3x,'* 18 *  Surface Water Density [kg/cu.m] - ',F20.8,/,
     +3x,'* 19 *  Depth of Pycnocline [m] - ',F20.8,/,
     +3x,'* 20 *  Fresh Oil-Water Int Tension [N/m] - ',F20.8,/,
     +3x,'* 21 *  Oil-Water Int Tension Constant [INTC1] - ',F20.8,/,
     +3x,'* 22 *  Fresh Oil-Air Int Tension [N/m] - ',F20.8,/,
     +3x,'* 23 *  Oil-Air Int Tension Constant [INTC2] - ',F20.8,/,
     +3x,'* 24 *  ASTM Distillation Constant [T] - ',F20.8,/,
     +3x,'* 25 *  ASTM Distillation Constant [A] - ',F20.8,/,
     +3X,'* 26 *  Time Interval For Data OUTPUT [hrs.] - ',f20.8,/,
     +3X,'* 27 *  Emulsification Delay [theta] - ',f20.8,/,
     +3X,'* 28 *  Time When Dispersant Applied [hr] - ',f20.8,/,
     +3X,'* 29 *  O-W Int Tension With Dispersant [N/m] - ',f20.8,/,
     +3X,'* 30 *  Duration Dispersant is Effective [hr] - ',f20.8,/,
     +,/,3x,'* 99 *     CHANGES COMPLETED  ',/)
         ENDFILE LUN
```

```
      RETURN
      END
```

```
      SUBROUTINE EVAP(FEVTK,FEVTN,DFEVTK,DFEVTN)
      COMMON /GEN/ TSTEP,TCOUNT,ZTHICK,ZTHIN,WINDS,OILD,OILV,TTK,TTKE
      COMMON /VAP/ AIRT,ASTMA,ASTMT
C
      RK=0.0015*(WINDS**0.78)
      DTTK=RK*TSTEP/ZTHICK
      TTK=TTK+DTTK
      DTTN=RK*TSTEP/ZTHIN
      DFEVTK=DTTK*EXP(6.3-(10.3/AIRT*(ASTMT+ASTMA*FEVTK)))
      DFEVTN=DTTN*EXP(6.3-(10.3/AIRT*(ASTMT+ASTMA*FEVTN)))
C
      FEVTK=FEVTK+DFEVTK
      FEVTN=FEVTN+DFEVTN
C
      RETURN
      END
```

```
      SUBROUTINE EMULS(WW,EMULD,EMULV,SURDEN)
      COMMON /GEN/ TSTEP,TCOUNT,ZTHICK,ZTHIN,WINDS,OILD,OILV,TTK,TTKE
C
      IF(TTK.LT.TTKE)GO TO 99
      DWW=2.0E-06*(WINDS+1.0)**2*(1.0-1.33*WW)*TSTEP
      WW=WW+DWW
C
      EMULV=OILV*EXP(2.5*WW/(1.0-0.65*WW))
      ZTHICK=ZTHICK/(1.0-WW)
      EMULD=OILD*(1.0-WW)+SURDEN*WW
C
      GO TO 100
99    EMULV=OILV
      EMULD=OILD
100   RETURN
      END
```

```
      SUBROUTINE SPREAD(ATHICK,ATHIN,ADIFF,SIGMA,OILPP,WATERT,SFACT,
     +IDIS)
      REAL LDIFF
      COMMON /GEN/ TSTEP,TCOUNT,ZTHICK,ZTHIN,WINDS,OILD,OILV,TTK,TTKE
C
      C=-.003
      IF(SFACT.EQ.1.AND.IDIS.EQ.1)C=-1.0*ZTHICK
      IF(SFACT.EQ.2)C=0
      DTHIN=SFACT*(ATHIN**.33)*EXP(C/ZTHICK)*TSTEP
       DTHICK=150.*(ZTHICK**1.33)*(ATHICK**0.33)*TSTEP-(1.0E-06*DTHIN/
     +ZTHICK)
C
      IF(SIGMA .LE. 0.0) DTHIN=0.0
      IF(OILPP.GE.WATERT) DTHICK=0.0
C
      ATHICK=ATHICK+DTHICK
      ATHIN=ATHIN+DTHIN
C
      LDIFF=3.12E-03*TCOUNT**1.17
      ADIFF=3.1415*(LDIFF**2)
C
      RETURN
      END
```

```
      SUBROUTINE DISPRS(FDTK,FDTN,OWINT,EMULD,EMULV,TNOILV)
      REAL LMTK,LMTN
      COMMON /GEN/ TSTEP,TCOUNT,ZTHICK,ZTHIN,WINDS,OILD,OILV,TTK,TTKE
C
      DROW=1025.-EMULD
      DROW2=1025.-OILD
      DUMMY=((WINDS/8.)**2)*2.4E03/(OWINT*EMULV*DROW)
C
      LMTK=1.16E-06*DUMMY*0.001/ZTHICK
C
      SHUT=EMULV
      IF(TNOILV.GT.EMULV)SHUT=TNOILV*DROW2/DROW
      LMTN=1.16E-06*DUMMY*0.001/ZTHIN*(EMULV/SHUT)

C
      FDTK=LMTK*TSTEP
      FDTN=LMTN*TSTEP
C
      RETURN
      END
```

RESULTS FOR FIGURE 33

```
* 1 *  Oil Volume (Cu M) -                      1000.00000000
* 2 *  Duration of Spill (Sec) -                1200.00000000
* 3 *  Wind Speed (M/S @ 10 M) -                5.00000000
* 4 *  Air Temperature (K) -                    276.00000000
* 5 *  Water Temperature (K) -                  273.00000000
* 6 *  Fresh Oil Density (Kg/cu M) -            990.00000000
* 7 *  Standard Density Temperature (K) -       273.00000000
* 8 *  Density Constant  (DC1) -                71.69999695
* 9 *  Density Constant  (DC2) -                .69999999
* 10 * Fresh Oil Viscosity (mPas) -             25.00000000
* 11 * Standard Viscosity Temperature (K) -     273.00000000
* 12 * Viscosity Constant (VC1) -               5.09999990
* 13 * Viscosity Constant (VC2) -               3040.00000000
* 14 * Fresh Oil Pour Point (K) -               233.00000000
* 15 * Pour Point Constant (PPC) -              0.00000000

* 99 *    CHANGES COMPLETED

* 16 * Swell Height (m) -                       3.00000000
* 17 * Swell Length (m) -                       200.00000000
* 18 * Surface Water Density (kg/cu.m) -        1015.00000000
* 19 * Depth of Pycnocline (m) -                10.00000000
* 20 * Fresh Oil-Water Int Tension (N/m) -      .02100000
* 21 * Oil-Water Int Tension Constant (INTC1) - 0.00000000
* 22 * Fresh Oil-Air Int Tension (N/m) -        .03000000
* 23 * Oil-Air Int Tension Constant (INTC2) -   0.00000000
* 24 * ASTM Distillation Constant (T) -         471.00000000
* 25 * ASTM Distillation Constant (A) -         370.00000000
* 26 * Time Interval For Data OUTPUT (hrs )     12.00000000
* 27 * Emulsification Delay (theta) -           0.00000000
* 28 * Time When Dispersant Applied (hr) -      1000.00000000
* 29 * O-W Int Tension With Dispersant (N/m) -  .00010000
* 30 * Duration Dispersant Is Effective (hr) -  .12500000

* 99 *    CHANGES COMPLETED
```

TIME (HRS.) - 12

	AREA	THICKNESS	VOLUME	TF EVAP	TotVolEvap	F DIS	TotVolDis
THICK	315324.	.002256	711.529	.1781	152.254	.0000	31.032
THIN	1657394.	.000001	1.376	.0002	19.265	.1796	84.545
	1972718.		712.905		171.519		115.576
BY OKUBO-	2138564.						

OIL PROPERTIES

	DENSITY	VISCOSITY	WATER CONTENT	THICKNESS
OIL :	1003.	62.		.002256
EMULSION :	1012.	2188.	.7400	.008679

BLOB D	OW DEPTH	MS DEPTH	F TEN CM	F 10-METRE	F DEEP	THETA
0.0000	0.000	.000	0.0000	0.0000	0.0000	61065.

. . . .

TIME (HRS.) - 24

	AREA	THICKNESS	VOLUME	TF EVAP	TotVolEvap	F DIS	TotVolDis
THICK	358116.	.001485	531.799	.2562	201.325	.0000	36.412
THIN	2624280.	.000001	2.327	.0001	29.128	.1222	199.009
	2982397.		534.126		230.453		235.422
BY OKUBO-	10827636.						

OIL PROPERTIES

	DENSITY	VISCOSITY	WATER CONTENT	THICKNESS
OIL :	1008.	92.		.001485
EMULSION :	1013.	3639.	.7517	.005980

BLOB D	OW DEPTH	MS DEPTH	F TEN CM	F 10-METRE	F DEEP	THETA
2.0886	.169	3.251	.0660	.4290	.5049	190729.

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TIME (HRS.) - 36

	AREA	THICKNESS	VOLUME	TF EVAP	TotVolEvap	F DIS	TotVolDis
THICK	358116.	.001051	376.316	.3035	222.935	.0000	40.696
THIN	3171850.	.000001	2.875	.0001	31.672	.1033	325.507
	3529966.		379.191		254.607		366.203
BY OKUBO-	27963302.						

OIL PROPERTIES

	DENSITY	VISCOSITY	WATER CONTENT	THICKNESS
OIL :	1012.	118.		.001051
EMULSION :	1014.	4641.	.7519	.004235

BLOB D	OW DEPTH	MS DEPTH	F TEN CM	F 10-METRE	F DEEP	THETA
1.6378	.316	5.341	.0393	.2912	.6695	371884.

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TIME (HRS.) - 48

	AREA	THICKNESS	VOLUME	TF EVAP	TotVolEvap	F DIS	TotVolDis
THICK	358116.	.000658	235.634	.3427	234.919	.0000	44.393
THIN	3359652.	.000001	3.081	.0000	31.734	.0904	450.238
	3717768.		238.715		266.654		494.632
BY OKUBO-	54820612.						

OIL PROPERTIES

	DENSITY	VISCOSITY	WATER CONTENT	THICKNESS
OIL :	1015.	144.		.000658
EMULSION :	1015.	5669.	.7519	.002652

BLOB D	OW DEPTH	MS DEPTH	F TEN CM	F 10-METRE	F DEEP	THETA
1.3410	1.488	10.000	.0103	.0880	.9017	643246.

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OIL HAS SANK TO PYCNOCLINE OVER AN AREA OF- 358116. sq. metres AFTER 49.78 hours.